RIVER BASIN SIMULATION AS A MEANS OF DETERMINING OPERATING POLICY FOR A WATER CONTROL SYSTEM

By

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A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1973

ACKNOWLEDGMENTS

My graduate study has been rewarding and enjoyable. Many people are responsible, and to them I feel a debt of gratitude.

My greatest debt is to my wife and sons for being so patient with my indulgence. Suzanne's understanding nature and day-by-day vote of confidence has been invaluable. I thank my sons, Jeffrey, Gregory, Douglas, and Jason, for their understanding at being fatherless on many occasions important to them.

Richard Conner as Chairman of my Supervisory Committee has provided academic and technical guidance in a masterful way, making the preparation of this dissertation exciting and enjoyable. More than this, he has provided a warm friendship in trying times. Fred Tyner as Chairman in the early stages of my study furnished good advice. John Reynolds' experience with the technical aspects of the dissertation problem was helpful. Richard Fluck and Leo Polopolus critically reviewed the manuscript. For these contributions and many left unmentioned, I wish to thank the members of my Supervisory Committee.

Special appreciation is extended to Sheriar Irani for his able assistance with the computer programming. Special thanks also go to Pam Bunde and Carolyn Crook for their help with the preliminary draft typing in those last hectic days.

K. R. Tefertiller, the faculty, and my fellow graduate students of the Department of Food and Resources Economics have contributed

greatly in making this study period significant. My friends in the Department of Agricultural Engineering have done likewise. To all I am grateful.

This study could not have been accomplished without the financial support of the Office of Water Resources Research, U. S. Department of Interior, through the Florida Water Resources Research Center, the Central and Southern Florida Flood Control District, and the Florida Agricultural Experiment Stations. Likewise the University of Florida Computing Center provided the means of handling such a study.

To the many unmentioned others, I am grateful.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate Council of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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June, 1973

Chairman: J. Richard Conner
Major Department: Food and Resource Economics

The handling of water management problems requires integration of technical detail with the social consequences of water availability and control. Nature provides the water, and man attempts to deal with the variable supply and put it to his use. This study suggests simulation as a means of considering alternative policies for an existing water control system. Specifically, the problem of dealing with the formulation of water management policy for the area of south Florida within the Central and Southern Florida Flood Control District was undertaken.

The objectives of this study were to (a) propose an organizational framework in which hydrologic, economic, and institutional aspects of the region may be used in policy development, (b) develop a simulation model which includes the salient hydrologic, economic, and institutional features of the Upper Kissimmee River Basin to serve as a guide, (c) demonstrate the usefulness of the simulation model in policy evaluations, and (d) determine the appropriateness of the approach for use in policy problems encountered when dealing with a large region.

A framework merging the technological aspects of the hydrology, water management, and economic water use activities with the social attitudes of the region was suggested. The essence of the framework is the use of simulation models in conjunction with an evaluation process by a group representing the people of the region.

A first-generation simulation model of the hydrologic phenomena and water-oriented activities in the Upper Kissimmee River Basin was developed. Models of the surface water management system, the water use activities, and the institutional constraints were interfaced with rainfall and watershed runoff models. The model of the surface water management system included sub-models of the gate-type control structures, the canal systems, and the water storage system. The water use activities model was made up of sub-models for crop irrigation, residential water consumption, and property flooding. The institutional constraint model included sub-models of lake surface elevation, consumptive withdrawal, and minimum flow regulations.

The model uses as input rainfall over time, which is transformed into watershed runoff in the form of a time series with a short interval. The runoff values thus incorporate the stochastic properties of the rainfall. The water management model, operating under a given set of policy constraints, attempts to cope with the hydrologic events. The hydrologic variability is passed on to the water use activities in the form of water in storage and lake surface elevations. The water use activities model calculates the levels of the activities and the benefits accruing.

The usefulness of the model was demonstrated by considering four policy areas: (a) temporal and spatial storage of surface water,

(b) consumptive withdrawals, (c) minimum flows, and (d) land and water use patterns. In all demonstrations the results were sets of water flow data, lake surface elevations, water use activity levels, and dollar benefits. These data provided the information used in the policy evaluation by the decision makers.

The methodology, because of its detailed approach, lends itself to the refinement of operational policy for individual basins. The method could be extended to cover an area as large as the entire Central and Southern Florida Flood Control District, but, rather than construct one large model, it would be best to work on individual basins. Each could then be tied together by a large, much less detailed model of the entire region. This model could be a linear programming model or an aggregate simulation model and would consider broad policy alternatives. The reduced number of alternatives could be submitted to the individual basin models and shaped into final operating policy for each basin.

CHAPTER I

INTRODUCTION

The Problem

An Overview

Man, from the very beginning, has had water problems. He developed a rudimentary agriculture where water was available in desired quantities but failed in areas of extremes. As time passed, he learned to control the effects of nature's extremes and civilization flourished.

Twentieth-century man still finds himself beset by water problems. In many parts of the world, these problems involve simply water for food and fiber production. In the advanced nations, however, other problems have arisen which often bring conflict among water users. Water is now used for recreation and aesthetics, waste disposal, and preservation of natural ecological systems as well as the traditional crop production.

Florida is encountering many such problems, and the situation here is dramatic because of the oscillation between too much water and too little water. The users of water in this state -- agriculturalists, naturalists, recreationists, industrialists, and municipalities -- often find themselves in disagreement as to how water should be used. One need only consult the daily newspaper to see evidence of the running debates presently underway.

Recent legislation, primarily the Florida Water Resources Act of 1972, has been enacted to create a governmental framework in which these

problems can be attacked. Foremost in this framework is the broadening of the powers of the Department of Natural Resources and the creation of five water management districts which would take in the entire state land area and water resources. The portion of south Florida under the management of the Central and Southern Florida Flood Control District is typical of most water management areas and, because of the high degree of urbanization, agricultural development and a unique natural environment, has been facing many of the problems the new water management districts will confront. This area and the management of it may serve as a guide in establishing the new organizations.

The Central and Southern Florida Flood Control District (FCD), a statutory agency, was created in 1949 and given responsibility for managing the water resources in this location, with the major objective of flood control. To accomplish this, a physical system consisting of a complex of canals, levees, pumping stations, spillways, navigation locks, and retention basins was constructed in the 15,700-square-mile area in the intervening years. This system has been operated with criteria which were derived primarily for flood control by the U. S. Army Corps of Engineers in the early years of the project.

Many groups representing water users in the District are concerned about water allocation and believe the present operational management does not provide maximum benefits. Each wants to have its needs met. The property owners and business interests want flood protection, the municipalities and agriculturalists want a consistent water supply, the recreationists want quality water, and the environmental groups want water for the natural systems such as the Everglades and the

coastal estuaries. The FCD, responding to water-related changes in the area, has taken on other management responsibilities which include water conservation, water supply, preservation and enhancement of fish and wildlife, improvement of navigation, and public recreation.

The FDC realized that operational "rules" based on flood control design criteria and previously existing demands can fall short of generating maximum benefits when the complexion of land use, drainage, urbanization, pollution, and industrialization, within the project boundaries, changes. Desiring to develop a rational system of water management which would better satisfy the various users of water, the FDC has undertaken a program to derive new criteria by which to operate. It is thought that a model incorporating the salient features of the hydrology and the various water-using activities of the area would give greater insight into the interaction among users and thus greater knowledge of how to manage the system. Such a model would not be possible immediately because of the lack of knowledge about both the hydrologic characteristics and the water use activities. The model, instead, could evolve.

A logical first step in developing a model which involves such complexities is to consider an area smaller than the total 15,700 square miles and the use of this as a pilot for the larger study. The Upper Kissimmee River Basin can be studied since sufficient information is available to prepare a simulation model of the hydrology and the economic activities in the area. The model would provide guidelines for water allocation and management by reflecting the interaction of the various economic activities and the effect the stochastic nature of the hydrology has on benefits accruing to the area due to the use of water. It should

be noted here that the model could be used to generate a response surface which could be explored with an optimum-seeking method. But the main purpose of the model (rather than being to obtain an optimal operation policy) will be to provide greater knowledge of the workings of the system much as an experimental apparatus is used in the physical sciences. Potential operating procedures obtained from the simulation model will then be considered by the FCD governing board and a policy derived. The policy most likely will not be optimal in an economic sense, and it will probably not be wholeheartedly supported by any group, but it will reflect their point of view better than a policy based solely on economic optimality or on flood prevention.

The general purpose of this study is thus to (a) prepare a first-generation simulation model of the economic activities in the Upper Kissimmee River Basin and interface it with a hydrologic model of the area and (b) evaluate the potential of this model in the determination of operational policy.

Earlier Modeling Work

The majority of previous economic analyses of river basins have dealt with the design of water resource systems. These studies have been primarily concerned with determining the optimum size and combination of structures to maximize benefits given an operating procedure. This procedure specified the allocations among areas. The present study deals with the case in which a water resources system has been completed and in use for a period of time. No major physical changes in the water management system are possible but many changes in land/water use

patterns have evolved. Now only the operating procedure can be modified to move to a point of higher net benefits.

Two approaches have been employed in the investigation of water resources systems and both are being used to study the allocation of water in the Upper Kissimmee River Basin. Reynolds and Conner [20] are using mathematical programming in the form of a dynamic linear programming model. This model will determine the optimal temporal allocation of water among alternative uses and watersheds. The pertinent literature dealing with this approach was reviewed in their project statement. The present study will utilize simulation as an alternative method.

Simulation has several advantages. Foremost is the ability to readily change formulations and parameters, thus allowing the model to be viewed as an apparatus with which experiments can be performed. Changes in the availability of water and the physical, political, and institutional constraints are easily handled. The model is not limited to the optimization of a given objective function but can be used to consider a number of different objectives. The necessity of systematically laying out the economic activities and the physical movement of water in the model assists in providing greater insight into the real system. This, coupled with the ability to handle many variables and nonlinear formulations, gives simulation much intuitive appeal for use in water resource studies.

Probably the best known of the early simulation models is that of the Harvard Water Program [14] in which a hypothetical river basin system is simulated. Twelve design variables consisting of reservoirs, power plants, irrigation works, target output for irrigation and electrical energy, and specified allocations of reservoir capacity for flood

control were considered. The economic benefits of the system were determined on the basis of use and control of water moving through the system. The design of the system was obtained both by sampling from the many combinations of design variables and the use of optimum-seeking methods to determine the design that provided maximum net benefits. The Harvard Water Program later used this approach in a model of the Delaware River Basin and Hufschmidt and Fiering [12] applied it to the Lehigh River Basin in Pennsylvania.

The Battelle Memorial Institute used a somewhat different approach in their work on the Susquehanna River Basin [10]. This study was concerned with the economic interrelations existing in the river basin and attempted to delineate the factors influenceing the economic growth of the area. The entire area was broken down into sub-regions, each described by a series of equations which related the interrelations and feedbacks of three major factor groups: (s) size and distribution of the population, (b) kind and level of employment, and (c) water availability and control. The sub-factors concerning water were water quality, water supply (agriculture, urban, and industrial), water for recreation, flood control, and water for electric power generators. The researchers saw simulation as an evolutionary process where an operational model is developed, then continually modified as time passes. The model was seen not as a tool for finding an optimal solution but as the key to a cohesive planning effort where the model served as a central focus by relating parts of the study and tending to keep them in balanced perspective.

Bathke [1] developed a simulation model of a simplified river basin in which he included hydrologic risk due to the variability of

rainfall and evaporation. Actual flow data from the South Concho River for a 39-year period were used to develop a response surface relating the variables. From this the optimal combination of reservoir capacity and irrigation project size was obtained by selecting the maximum total net benefit combination. Conner [5] extended this work to include the full effect of the risk element inherent in the system by considering the water users' reactions to risk and the effects of these reactions on optimal levels of the design variables.

The Corps of Engineers has realized the need to investigate the operation of existing water resource systems and has initiated a simulation study of the Arkansas-White-Red River system. The major purpose of the 23 reservoir projects located in the three river basins was initially power generation. The Corps' simulation is a hydraulic model in which the operational rules can be varied and results are evaluated on how well the operational objectives, primarily power generation, are met. A major problem in the study has been the inability to quantify the operational objectives for the existing system. There was no way to compare operational procedures when competitive uses of water were considered [7]. No attempt was made to simulate the economic activities associated with water use and determine the dollar benefits accruing to operational procedures.

Bredhoeft and Young [4] used simulation in the consideration of temporal allocation of ground water. The objective was to determine operational procedures for an existing irrigation system over a ground water basin. Water level in the basin was the connection between an economic and a hydrologic model.

Packer et al. [16] simulated the hydrologic-economic flow system of an agricultural area in Utah. The hydrologic characteristics of the Cache Valley were simulated first with an analog program and then as a digital program. The physical management system was taken as given and different management techniques were investigated. The only use of the water in agriculture, and net income accruing to the sector because of water use was the measure of management effectiveness. The link between the economic and hydrologic system was the production function, which related the actual evapotranspiration to the yield of the crop, while other variables affecting crop production were assumed to be relatively constant.

This literature and other peripheral works give insight into the approaches that can be used in the development of the hydrologic and economic simulation models for the Upper Kissimmee River Basin. It does not provide the guidelines that are needed for the development of operational procedures that provide an acceptable allocation of water to the various users over time. The next logical step is to develop a methodology that can provide tentative answers to the difficult allocation problems.

Management of Existing Systems

The planning and design studies mentioned above dealt primarily with determining the number, size, and location of components within the system to meet certain functional objectives. Generally, simplistic operating rules, independent of system configuration and invariant from alternative to alternative, were used resulting in operating policy being ignored as a planning or design variable. This was an adequate approach

for the planning and design of the system but, as soon as a significant number of components are completed, operating policy as a variable becomes important.

Simplifications were needed in the design problem to be able to deal with long periods of time and the resulting uncertainty. It was necessary to hypothesize how the system would operate and how water would be allocated for the life of the project. When the system is completed, however, the managing staff must deal with changing multipurpose operational objectives with which daily operations must be compatible. Emphasis is no longer on the very long-range operational policy; the day-to-day, month-to-month, year-to-year operation is now the major concern.

The activities and hydrology of the region are recognized to be dynamic, not static. Land and water use patterns are continuously modified by new crop plantings, livestock operations, urban development, recreational enterprises, and numerous other man-conceived ventures. Various other groups object and want water to maintain the natural system and wildlife. Conflict arises and pressure is applied to the institutions dealing with water management. Thus, public opinion points out that new operational objectives must be considered and integrated into the day-to-day operation of the system. The question is, how does the responsible agency deal with these varying influences and manage the system so as to provide the highest possible benefits to society as a whole?

Modeling, such as was used in the design studies, appears to be a partial answer. However, now the real world must be dealt with, not a hypothetical world that is to exist in the distant future. The models must incorporate the salient features of the hydrology, the water

management system, the economic activities, and the constraining institutions if the necessary interactions are to be considered adequately. Through experimental use, models can provide insight into the effects of potential operating policies. Changes in land and water use, economic activities, and institutions likewise can be incorporated into the models and their influences examined.

Objectives of the Study

Management of water resource systems is difficult under conditions where hydrologic variation is the major concern and water use activities are essentially static. In situations where man's activities are expanding at a phenomenal rate, also, intelligent management decisions become nearly impossible. The multitude of interactions are beyond the comprehension of the human mind. Computer simulation models have been used in other fields to extend man's analytical ability. It is believed that modeling can assist in the formulation of water management policy in south Florida.

Therefore, the objectives of this study are to

1. Propose an organizational framework in which hydrologic, economic, and institutional aspects of the region are used in policy development. The ability to meet long-term social goals depends upon the day-to-day physical management and use of water. This, in turn, is dependent on the water management policies in effect. So, in policy selection a framework incorporating feedback on the consequences of proposed policies is needed.

2. Develop a simulation model which includes the salient hydrologic, economic, and institutional features of the Upper Kissimmee River Basin. More specifically, develop and interface models of rainfall occurrence, runoff quantities, surface water management, water use activities, and institutional constraints.
3. Demonstrate the usefulness of the simulation model in policy evaluations. Policies concerning spatial and temporal storage of surface water, consumptive use withdrawals, minimum streamflows, and land and water use patterns will be considered.
4. Determine the appropriateness -- from the standpoint of validity of the models, data requirements and availability, and cost of operation -- of such an approach for use in policy problems encountered when dealing with a large region such as the Central and Southern Florida Flood Control District.

CHAPTER II

THE PRESENT AND FUTURE SYSTEM

Man's Dominance

The southern portion of the Florida peninsula was originally an area where the most striking feature was water. The region just south of present day Orlando and east of the central ridge was a large, flat, swampy, pine forest with many small and large shallow lakes. In times of heavy rains -- in the summers and early fall -- the lakes would overflow their banks and flow in large sheets southward to other lakes and into the Kissimmee River, a wide, very flat flood plain which remained swampy all year. The water next moved into Lake Okeechobee, the large body of water that dominates south Florida. Water from heavy rains swelled the lake causing it to overflow the banks southward into a sea of sawgrass covering virtually the entire southern tip of the peninsula. Wildlife was profuse. Reptiles, mammals, and birds were tied to the water in a fine balance. The fresh water moving into the salt water of the Atlantic and Gulf of Mexico formed brackish estuaries which were teeming with fish and shell fish.

The area remained uninhabited except for Indian hunting parties until the nineteenth century when a few hundred Seminole Indians escaping from white settlers in central Florida moved into the area. Later in the century, the state sold large blocks of the Kissimmee Basin to

individuals who drained the land and put cattle on it. At the turn of the century, crop farmers began to drain the muck lands below Lake Okeechobee. A small settlement, Miami, grew on the coastal sand ridge.

The early part of the twentieth century saw more farmers moving into the area just below Lake Okeechobee, and the towns of Belle Glade and Clewiston came into existence. In the twenties, storms swelled the lake causing great floods and thousands of deaths. At the same time, the Atlantic coast was experiencing a boom, in which speculators were buying and developing land to sell to people from the North. The warm tropical climate was now accessible by railroad.

The series of events caused strong pressure to control the water. The Federal Government began to dike Lake Okeechobee and to dig large canals to the coast,allowing great quantities of water to be released quickly into the Atlantic. Smaller canals laced the marshlands and tied into the larger system. Developers dug canals in the coastal areas to make way for homes. Drainage of the area below Lake Okeechobee continued through the 1960's. In the fifties, land owners above the lake were pressing to control the water in the Kissimmee River Basin. The river was channelized, canals were dug between the lakes and a number of control structures were built. Man now played a dominant role in south Florida.

The ability to control water opened the way to expansion of man's activities at an even greater rate. The population of the area is presently three million and is concentrated around Orlando in the Upper Kissimmee Basin and in a megalopolis running from Fort Pierce south to the Florida Keys. Tourist attractions in these areas swell the population each year. The population is expected to continue to grow. Crops

and native pasture now occupy much of the land, and expansion of improved pasture and citrus have taken place at a rapid rate.

The Management Organization

The Central and Southern Florida Flood Control District's role has expanded as south Florida grew and now includes the following responsibilities:

1. Flood Control -- protection of life and property from floods and hurricanes is provided through the use of dikes, levees, canals, and pumping stations.
2. Water Conservation -- excess surface water is stored for beneficial use in dry times in a network of interconnected reservoirs including the Kissimmee River Basin, Lake Okeechobee, and 50 percent of the original Everglades, and ground water levels are maintained through management of the surface water.
3. Salt Water Intrusion Prevention -- water storage in the Everglades wilderness areas provides a head on fresh water necessary to prevent salt water intrusion into coastal well fields.
4. Fish and Wildlife Preservation -- through careful planing and operation of the physical system, water is provided to maintain the natural wildlife systems.
5. Everglades National Park -- water is provided from conservation storage areas to assist in restoring and maintaining natural conditions within the park.

6. Agriculture -- flood protection, drainage, and water supply are provided to foster efficient use of the farm lands in the District.
7. Recreation -- provides recreational areas throughout the District so stored water can be used for recreational activities.
8. Pollution Abatement -- through protective works and controls, the FCD is working to provide and maintain quality water.
9. Navigation -- small boat navigation is provided in canals whenever practical and economically feasible.

The FCD's organization is structured to reflect the prevalent attitudes of the people of south Florida. Policies are established by a nine-man governing board of local people appointed for four-year staggered terms by the governor and confirmed by the Florida Senate. Daily activities are carried out by a staff of 750 in engineering, operation and maintenance, planning, land, legal, financial, and administrative divisions. An executive director heads this organization.

The Florida Water Resources Act of 1972 makes the FCD one of five water management districts in Florida and greatly increases their power to carry out the above responsibilities. The district is granted authority to issue permits to all consumptive users of water except household (domestic) use. Broad powers are granted in the management and storage of surface water and procedures for imposing restrictions on water users in periods of water shortages are to be established to protect water resources from serious harm. The governing board with authorization of the Department of Natural Resources may determine,

establish, and control the level of water to be maintained in all canals, lakes, rivers, channels, reservoirs, streams, or other bodies of water controlled by the District. The board is also empowered to acquire fee title to real property and easements for flood control, water storage, water management, and preservation of wildlands, streams, and lakes. These powers, along with regulation of wells, will allow coordinated use of waters in the District.

The FCD, as an agency operating a complex physical system (see Figure 1) in an area in which user demands have become greater and more involved, has realized that more informed and versatile operational procedures may extend the project's performance beyond that which was originally anticipated. An approach which reflects the natural hydrology and the potential of the physical system in conjunction with the economic activities and institutional constraints occurring in the area is needed. Computer models are thought to be feasible and practical. They would feature the quantifiable characteristics of the hydrologic, physical management, economic, and institutional systems while the Governing Board would reflect the subtle nonquantifiable factors which must also be considered. The result would be a short-term operational policy compatible with long-term objectives but which is derived from greater knowledge of the interactions of the various systems than would be possible without the models.

The resulting operational policy would be programmed into daily execution. This system uses as input actual rainfall over the area which is automatically measured and the resulting data transmitted to the operations center by telemetry. Various models digest the information and determine a set of gate operations compatible with the short-term

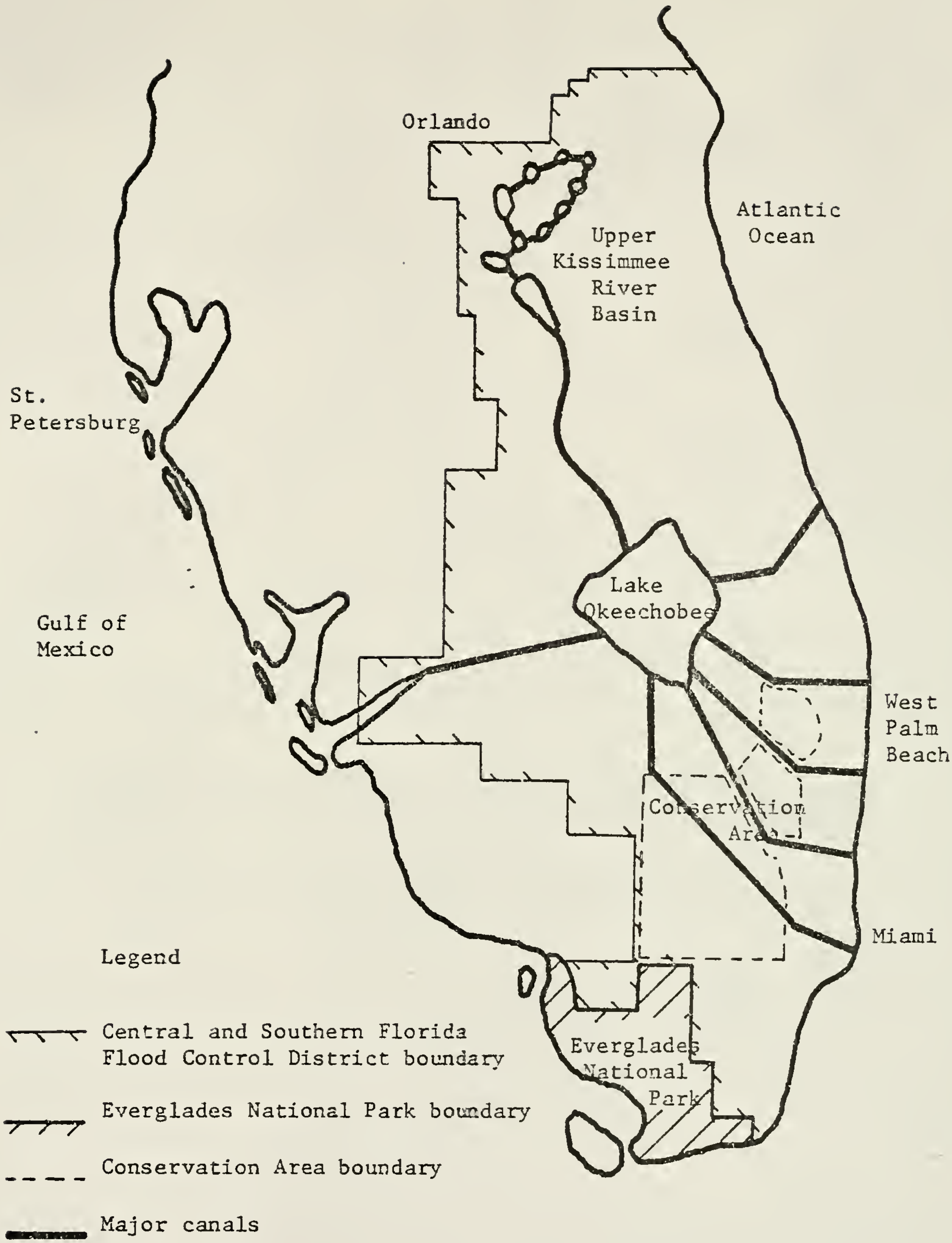


Figure 1. A schematic diagram of the FCD system in south Florida.

policy, and these in turn are beamed back to the field and executed.

Figure 2 illustrates a conceptual model designed to develop operational water management policy and then execute it by prescribing a short-term gate operation schedule. The manner in which the policy development side functions is as follows:

a) A proposed long-term regulation policy is specified. This could be in the form of a gate regulation schedule (rule curve), water use regulation, land use change, or any other modification.

b) This policy affects the form of the surface water management model or the institutional constraint model.

c) Hydrologic data are the primary input to the surface water management model, and the output is a set of lake surface elevations, the lake system states.

d) The lake system states are input to the economic activities model, which gives as output the levels of the various water use activities and the net dollar benefits accruing to various activities as a result of the regulation policy.

e) The lake states, benefit states, and institutional constraints provide information on the reasonableness of the proposed regulation policy. If not accepted, the policy is modified in light of the evaluation results and another run is made.

f) If the policy is accepted, it is next evaluated by the Governing Board in the light of considerations that cannot be quantified. If rejected, modifications and a new series of runs are made until the policy is acceptable at the first level.

g) If accepted by the Governing Board, it becomes the short-term operational policy and is used in execution.

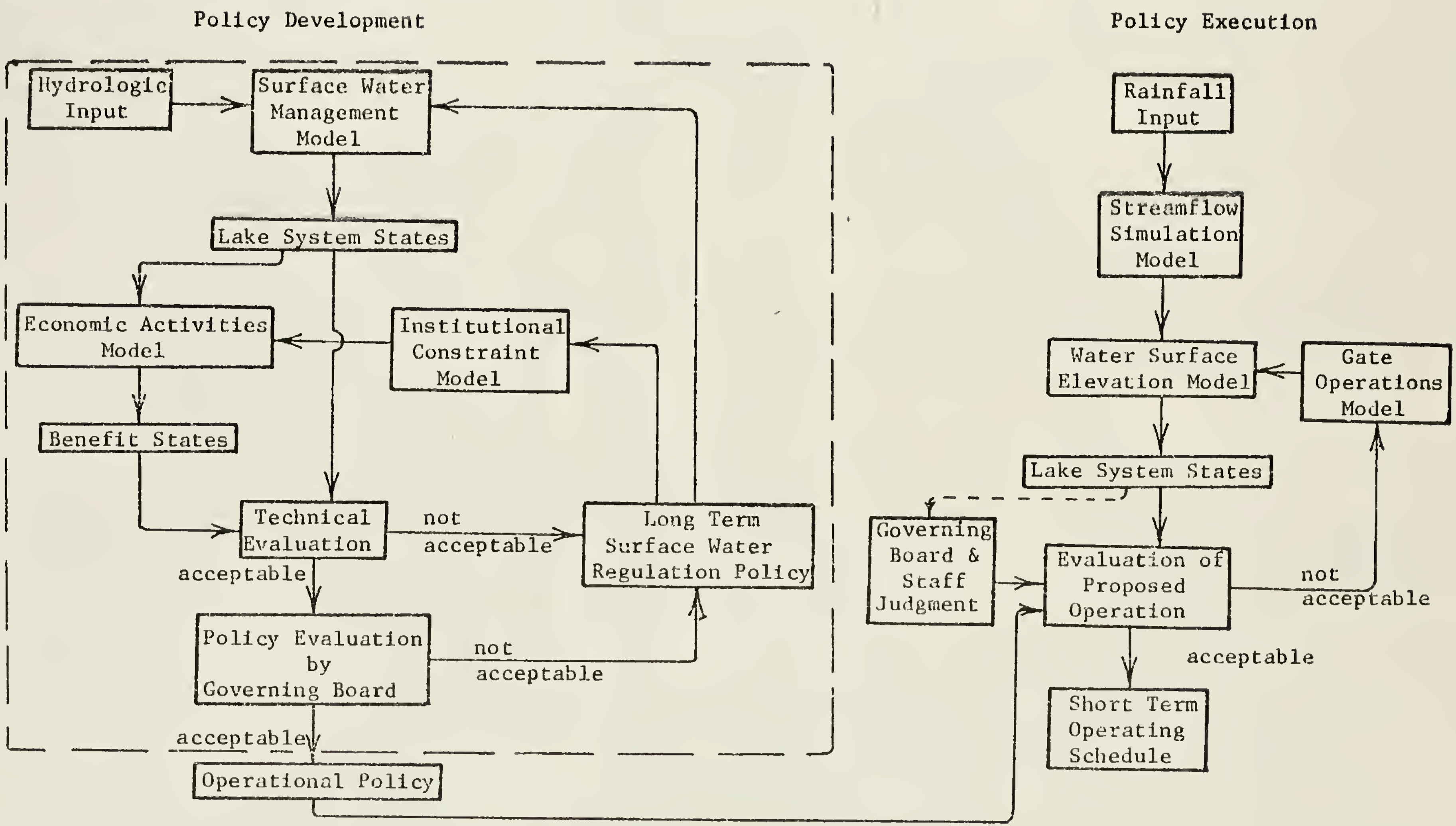


Figure 2. Operational water management policy and execution model.

The policy execution side functions in a similar manner.

a) Actual rainfall is continuously monitored and the data transmitted to the operations center via the telemetry system.

b) The rainfall data provide input to the streamflow simulator, which produces as output runoff into the lakes.

c) A set of gate operations is specified by the gate operations model.

d) The gate operations and runoff values are the input to the water surface elevations model, which gives as output a set of lake surface elevations or the lake system states.

e) These states are evaluated in terms of what the short-term operational policy specifies. In addition, Governing Board and staff judgment can be used to establish evaluation criteria. If rejected, a new set of gate operations is specified.

f) If accepted, the set of gate operations becomes the short-term operations schedule.

The present study will investigate the decision-making procedure. More specifically, it will interface the various models involved and demonstrate the procedure by considering several types of policy changes. The Upper Kissimmee River Basin was selected as the study area because of the wealth of information available about the hydrology, water management system, and water use activities.

The Study Area

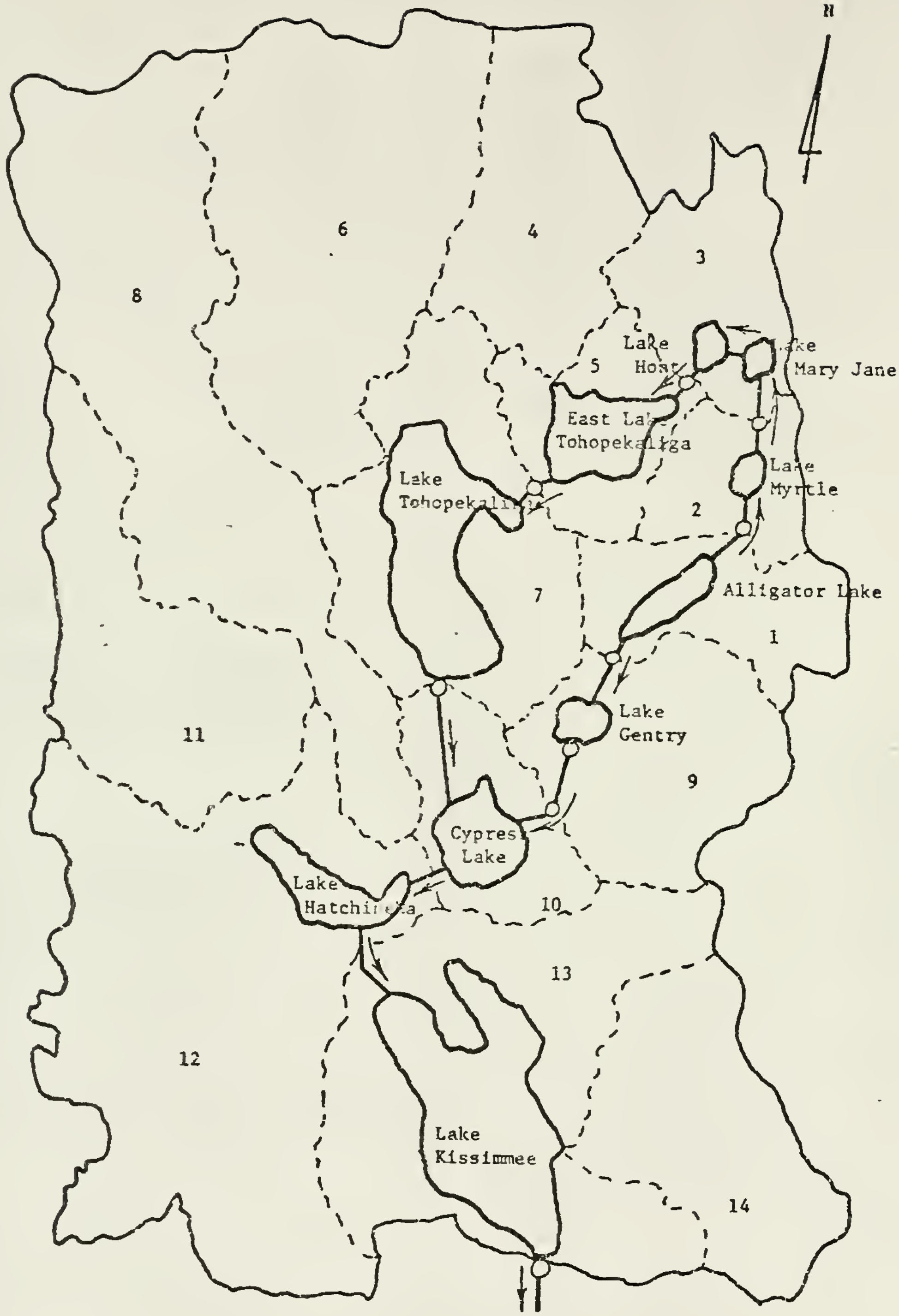
The Upper Kissimmee River Basin lies in the central part of Florida, as shown in Figure 1. The city of Orlando is located on the

upper boundary, with Walt Disney World and the towns of Kissimmee and St. Cloud nearby. The area is approximately 1600 square miles and topographically flat. The western boundary lies along the lower part of the central ridge of Florida. The central, eastern, and southern parts are very flat, with a slope seldom exceeding five feet per mile. The elevation runs from 100 feet in the upper end to 60 feet in the Lake Kissimmee district. The region originally had many shallow lakes and swamps with small streams running between them. Water moved south in a broad path and into the Kissimmee River, a poorly defined stream consisting of many small channels and a two-mile-wide swampy flood plain. This was the major source of water for Okeechobee and South Florida.

In recent times the basin has been greatly modified. Canals have been dug and control structures installed to control flooding. The major lakes are connected by these canals and small streams connect the smaller lakes. The basin consists of 14 sub-basins or watersheds that empty into ten major lakes. Figure 3 illustrates the location of these sub-basins, lakes, canals, and structures.

The predominant use of surface water has been for recreation. Swimming, water skiing, and boating are popular. Traditionally, the lakes have provided some of the best fishing in the South. The wildlife is not unique, but hunting of deer and fowl is good.

Drainage has made agriculture more profitable. The major portion of the land is unimproved native pasture; however, much improvement is underway. Pasture is not generally irrigated, but, when it is, ground water is most often used. Citrus is predominately on the western ridge and is irrigated with ground water. Increasing acreage is being developed on the flatwood soils and requires extensive drainage to



Legend

Upper Kissimmee River Boundary
Sub-basin boundary
Lake outline
Canal and control structure
Water flow

Figure 3. Upper Kissimmee River Basin.

provide 60 inches of unsaturated root zone. Most of these new plantings are irrigated with ground water, but groves near lakes and canals use surface water. Small quantities of vegetable crops and ornamentals are grown with ground water irrigation. Urban development in the northern part has been occurring at an ever-increasing rate. Walt Disney World has caused even greater growth in the area between Orlando and Kissimmee. The basin is a popular one for retired people as well as for tourists. These activities are, in general, placing heavy demands on the ground water and causing severe deterioration of surface water quality.

CHAPTER III

THE SIMULATION MODEL

Conceptual Aspects

The FCD, in developing an approach to study operational policy alternatives, must find one which will include the essence of the complexities involved in surface water management. The influence of the natural hydrology, the existing water management system, the water use activities, and the formal and informal institutions must be reflected. Inclusion of these is difficult because of the diversity in each but is essential if reasonable policy alternatives are to be found. This study suggests simulation as a means of considering various interactions. It is believed that many characteristics can be mathematically modeled, and quantitative parameters defined, to assist in policy evaluation. This, tied with the Governing Board's reflection of subtle nonquantifiable factors, would provide a means of evaluating policy alternatives. Figure 4 illustrates an information flow model, which is an expansion of the area enclosed by dotted lines in Figure 2 and provides a framework for a simulation approach.

The present study, more specifically, develops this conceptual model into an integral operational model. Rainfall data for the basin are either synthesized or obtained from historic records, then distributed over watersheds, and runoff determined. This in turn flows into the lakes and is stored or released through management of gate-type structures.

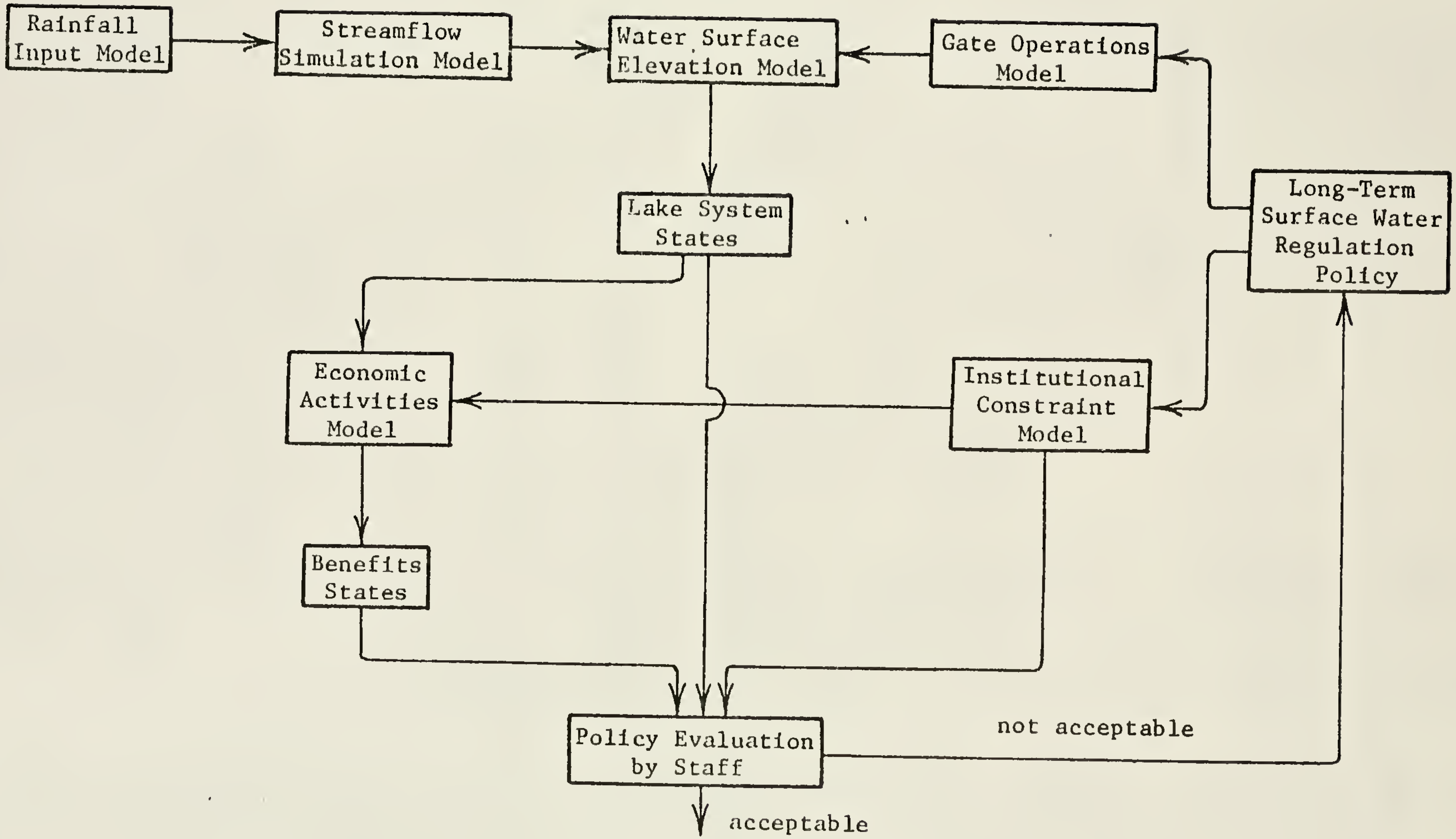


Figure 4. Water management information flow diagram.

Management criteria are specified by the long-term policies of the water management authority. Lake surface elevations are generated, providing information on the availability of water for various activities and the level of these is determined. The quantified economic benefits, along with the system states and the institutional considerations provide the input into the policy evaluation. This evaluation is a technical weighing of various parameters by the staff and is not itself modeled. It does, however, provide a feedback into long-term policy and suggests modifications.

The approach allows the water management authority to take initial hydrologic information on very short intervals and assess on the basis of long-term results the acceptability of the operational policy. This is accomplished by inputing rainfall at 12-minute intervals, thereby reflecting the natural variability. Runoff is determined at three-hour intervals and lake surface elevations at six-hour intervals. Economic activity levels are determined at varying intervals depending on the activity, and net benefits are totalled annually. Therefore, by operating the simulation, given a specific operational procedure, for an extended period of time, information is produced which is used in the policy evaluation.

The specific components or models making up the simulation are illustrated in Figure 4. Each of these, the rainfall model, streamflow model, water surface elevation model, gate operation model, and economic activities model will be discussed in detail. The institutional constraint model is incorporated in the other models.

Hydrologic Models

The rainfall input can be provided from either of two sources. The first, which is used in the present study, employs historic data from rain-gauging stations in the basin to determine the rainfall over each of the sub-basins. This is accomplished in two steps. Step one distributes daily rainfall values at a geographic point into 24-hourly values and then divides each hourly rainfall value into five equal parts, thereby obtaining rainfall values at two-tenths-of-an-hour intervals. The development of the relationships is based primarily upon the work of Pattison [17], which considers a well acknowledged characteristic of persistency in daily rainfall values. The distribution of rainfall values at each gauge station is determined by statistically estimating the hour of start of daily rain and the expected value of the hourly rainfall. Step two estimates the two-tenths-of-an-hour-interval rainfall values at grid points between the widely separated rain-gauging stations. This approach is based essentially upon a square grid system where the rainfall at any grid point or node is computed by applying an appropriate weighting factor. These factors for each node are based on the relative distances from the rain guages which are within a specified distance of the node of interest. From these two-tenths-of-an-hour values a single rainfall value for an entire sub-basin is computed by averaging the weighted values over the sub-basin. Sinha and Khanal [22] have described the two steps in detail and presented values for the Kissimmee River Basin.

The second source utilizes a stochastic model to synthesize daily rainfall input data. Rainfall at a point is a continuous hydrologic process which can be transformed into a discrete process with a given

time interval. Rainfall amounts observed during different, short time intervals (hours, days) are not independent events, and conditional probabilities for these events can be estimated. The daily rainfall process is similar to a Markov process. Due to these similarities, a first-order Markov chain has been used to simulate the daily rainfall process in the Kissimmee River Basin. Khanal and Hamrick [13] have reported the details of this approach and the results for the basin. Data from this source replaces the historic daily rainfall values obtained from the twelve gauging stations.

The sub-model for simulating streamflow from rainfall events involves using mathematical relationships for determining four broad activities of the hydrologic cycle. These are (a) infiltration, (b) water losses due to evaporation, transpiration, and deep ground water percolation, (c) recovery of water into the stream channel from soil reservoir and overland flow, and (d) routing the water from channel to watershed outlet. Figure 5 illustrates the relationship these activities have to each other. The mathematical functions used in the Kissimmee River Basin model have been developed by several researchers and are presented by Sinha and Lindahl [23].

The volume of water moving into the soil profile is found by empirical infiltration equations, which are primarily functions of soil moisture. These are evaluated at the beginning and end of a time interval. Water loss, water that reaches the ground surface but never appears at the watershed outlet, is the total of these activities. An empirical expression that reflects the fluctuations in depth to the water table is used to specify the evaporation loss. The rate of loss is assumed to never exceed the pan evaporation rate. Transpiration losses are assumed

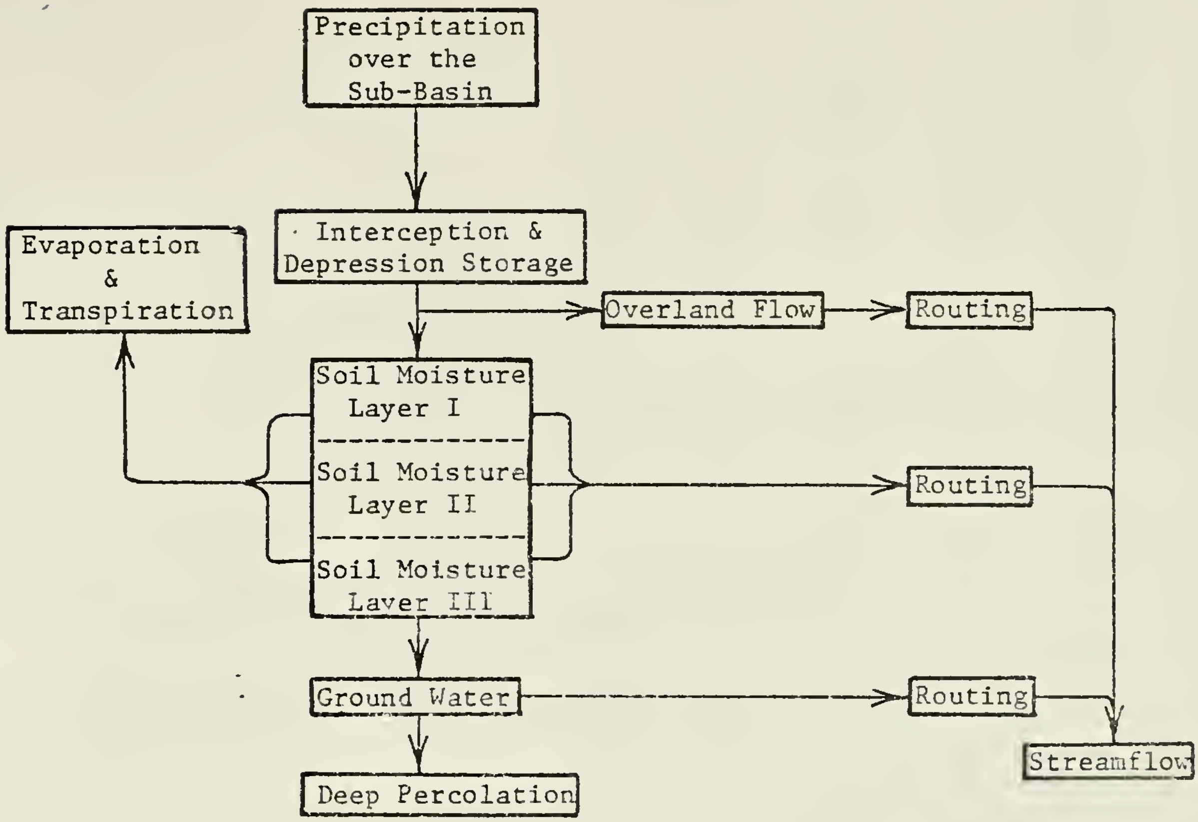


Figure 5. Flow diagram of streamflow simulation model.

to be primarily a function of pan evaporation and an overall growth index for the existing vegetation. Deep percolation is a function of the rate that gravitational water moves through the soil. Recovery of water into stream channels is from two sources, subsurface flow and overland flow. The mathematical relationships used to estimate the net surface discharge are based on the continuity equation and a storage/outflow expression developed empirically. These are solved in an iterative procedure. With the subsurface discharge available, total storage is obtained from a balance equation. Overland flow is the difference between the precipitation and infiltration when surface depression storage is full. Two routing equations have been used to obtain a time distribution of water

at the watershed outlet. The first was Nash's equation but this has been replaced by a simpler expression. It uses an empirical time constant associated with the source of the water -- surface or subsurface flow -- along with the average inflow and discharge at the beginning of the time interval. The present streamflow model uses rainfall input on a 12-minute interval and provides watershed discharge on a three-hour interval. This in turn is used as input into the water surface elevation management model.

The water surface elevation management model is the first point at which management decisions can be made and water output affected. Figure 3 shows the relationship of the actual watersheds, lakes, canals, and structures in the Upper Kissimmee Basin. The fourteen watersheds or sub-basins empty into the ten major lakes as presented in Table 1. Water in Alligator Lake can move north through Lake Myrtle and around the western chain, or south through Lake Gentry and into Cypress Lake, where the western and eastern flows come together. The water movement is then southward through Lake Kissimmee and down the Kissimmee River to Lake Okeechobee. This series of lakes, canals, and structures provides the management capability. By controlling the lake levels with nine control gates, water can be retained or released.

The management components of the Upper Kissimmee Basin can be generalized as shown schematically in Figure 6. Table 2 presents the nomenclature that is used for each component. Water can be retained in lakes 1-7 by management of the structures 1-9. The water discharged moves down one of the canals 1-13 and into the next lake. All runoff from the sub-basins entering the management system and all water withdrawals are assumed to occur only at the lakes. Lake Tohopekaliga is

Table 1. Relationships of sub-basins, lakes, and control structures.

Sub-basin	With Area[a]	Drains into Lake	Controlled by Structure
1	60.50	Alligator	S-58 and S-60
2	37.91	Myrtle	S-57
3	57.68	Mary Jane and Hart	S-62
4	89.67	East Tohopekaliga	S-59
5	52.93	East Tohopekaliga	S-59
6	185.66	Tohopekaliga	S-61
7	132.77	Tohopekaliga	S-61
8	198.75	Tohopekaliga	S-61
9	89.22	Gentry	S-63 and S-63A
10	119.63	Cypress	S-65
11	109.85	Hatchineha	S-65
12	197.78	Hatchineha	S-65
13	197.78	Kissimmee	S-65
14	94.70	Kissimmee	S-65

[a]Area is in square miles.

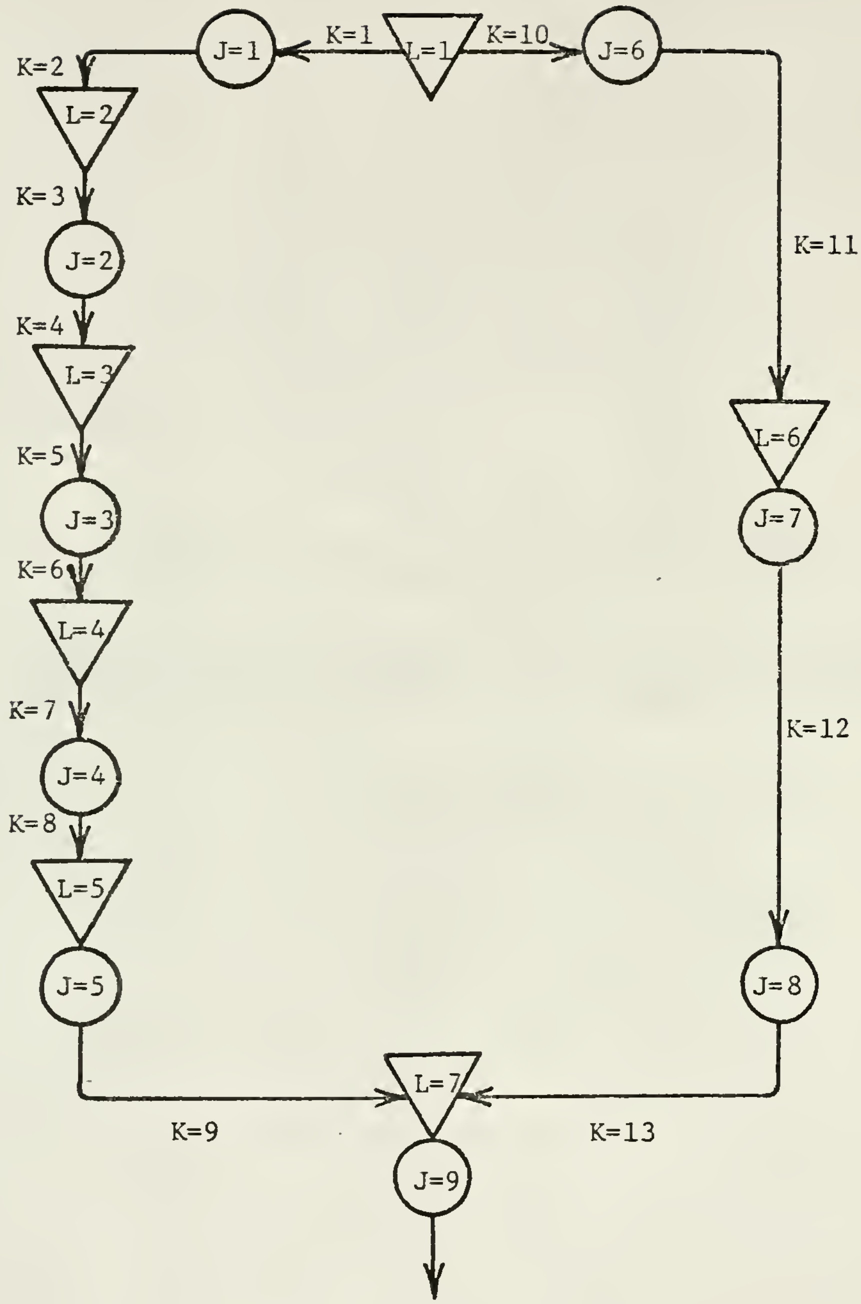


Figure 6. Schematic diagram of the Upper Kissimmee River Basin water management system.

Table 2. Symbols used to represent lakes, structures, and canals.

Symbol	Represents
L	Lake
1	Alligator
2	Myrtle
3	Mary Jane and Hart
4	East Tohopekaliga
5	Tohopekaliga
6	Gentry
7	Cypress, Hatchineha and Kissimmee
J	Structure
1	S-58
2	S-57
3	S-62
4	S-59
5	S-61
6	S-60
7	S-63
8	S-63A
9	S-65
K	Canal
1	C-32 above S-58
2	C-32 below S-58
3	C-30 above S-57
4	C-30 below S-57
5	C-29 above S-62
6	C-29 below S-62
7	C-31 above S-59
8	C-31 below S-59
9	C-35 below S-61
10	C-33 above S-60
11	C-33 below S-60
12	C-34 above S-63A
13	C-34 below S-63A

shown schematically in Figure 7 to illustrate typical water flows into and out of a lake. No return flows from consumptive uses are assumed.

The mathematical representation of water flow and management in this generalized system can best be handled by considering several fundamental activities. The major purpose of the model is to determine lake surface elevations at regular intervals, which is accomplished by determining the change in storage resulting in the flows illustrated in Figure 7.

The general flow equation is

$$QN_{L,i}=SUBQ_{L,i}+Q_{J_{up},i}-Q_{J_{down},i}-ACWS_{L,i}$$

where.

$QN_{L,i}$ = net flow rate for lake L in the time interval,

$SUBQ_{L,i}$ = total runoff flow rate into lake L,[1]

$Q_{J_{up},i}$ = flow rate into lake L from the upstream structure,

$Q_{J_{down},i}$ = flow rate out of lake L through the downstream structure, and

$ACWS_{L,i}$ = flow rate of consumptive withdrawals for lake L.

The lake surface elevation at the end of the present time interval, $ST_{L,i}$, is then a function of the water stored in the lake at the end of the previous time interval, $STOR_{L,i-1}$, and the net flow rate or

$$ST_{L,i} = s(STOR_{L,i-1},\ QN_{L,i}).$$

With the ability to obtain the lake structure elevation it is possible

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[1] Water entering the lake from rainfall and water leaving the lake by evaporation is included in $SUBQ_L$.

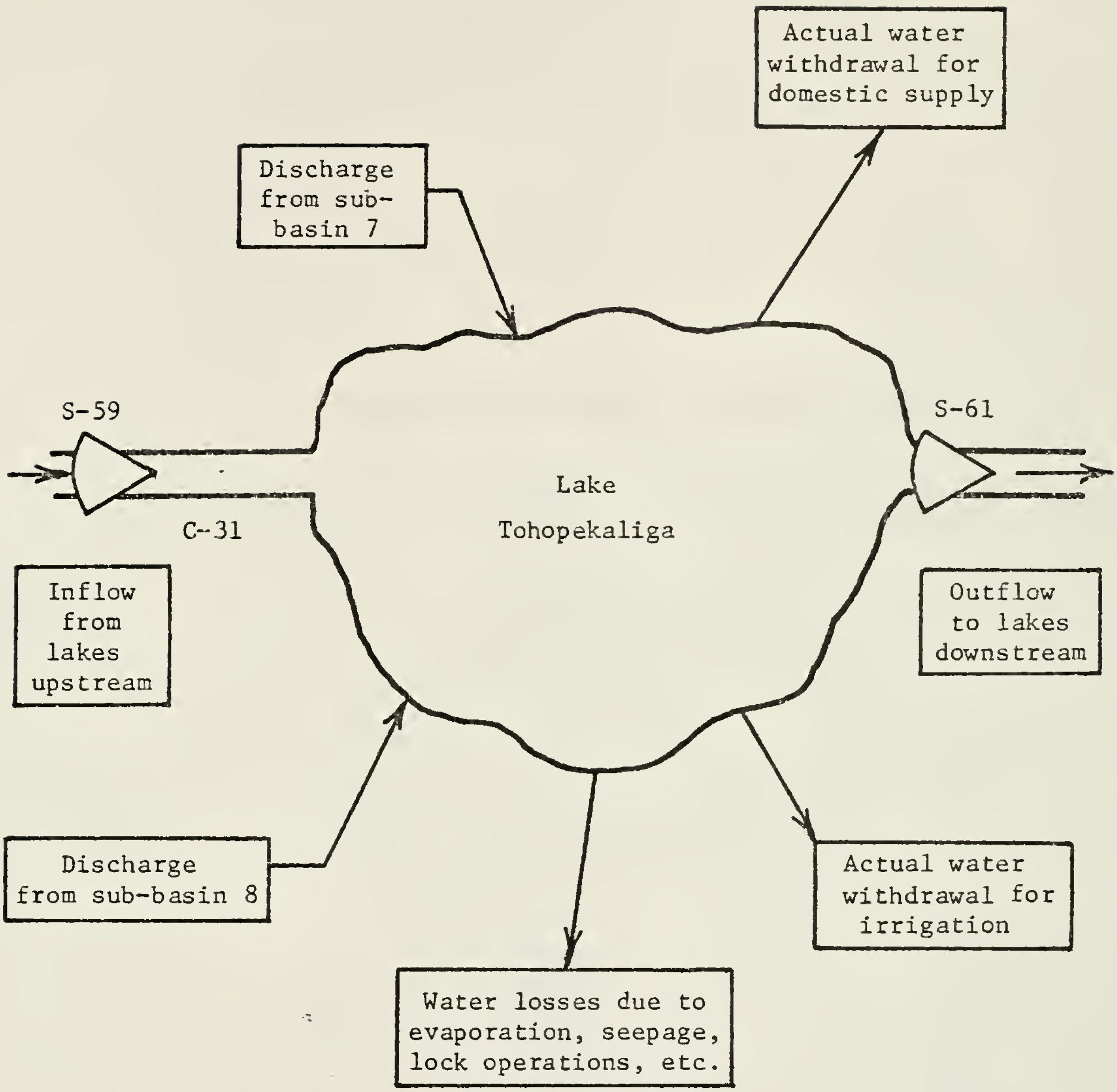


Figure 7. Water inflows and outflows for Lake Tohopekaliga.

to compare these with institutionally established desired lake surface elevations, $DST_{L,i}$. The manner in which these compare then specifies a set of gate manipulations or operations, $GO_{J,i}$. That is,

$$GO_{J,i} = g(ST_{L,i} -1, DST_{L,i}).$$

The gate operations and head and tailwater elevations at the end of the previous time interval, $HWS_{J,i-1}$ and $TWS_{J,i-1}$, respectively, allow calculation of the flow rates for the structure, $Q_{J,i}$. Or, mathematically,

$$Q_{J,i} = q(GO_{J,i}, HWS_{J,i-1}, TWS_{J,i-1}).$$

The consumptive withdrawal flow rate, $ACWS_{L,i}$, is an institutionally established function of the lake surface elevation and consumptive water needs, in this case irrigation, $IR_{L,i}$, and domestic consumption, $DC_{L,i}$. Implicitly,

$$ACWS_{L,i} = c(ST_{L,i-1}, IR_{L,i}, DC_{L,i}).$$

The sequence of calculations is shown in Figure 8, and consideration of the mathematical make-up of each component will be considered in this order. Initially sub-basin runoff values are provided as input data from the streamflow simulation model and a set of system states -- headwater, tailwater, and lake surface elevations are available from the previous time interval. The consumptive water withdrawals are determined from the irrigation and domestic consumption needs found in the water use model and the institutionally established withdrawal functions. In this study linear segmented functions specify the percentage of water needs that can be met using surface water. These are illustrated in Figure 9 for irrigation and domestic consumption.

The desired lake level is specified on any given day by an institutionally established linear segmented function, generally called the

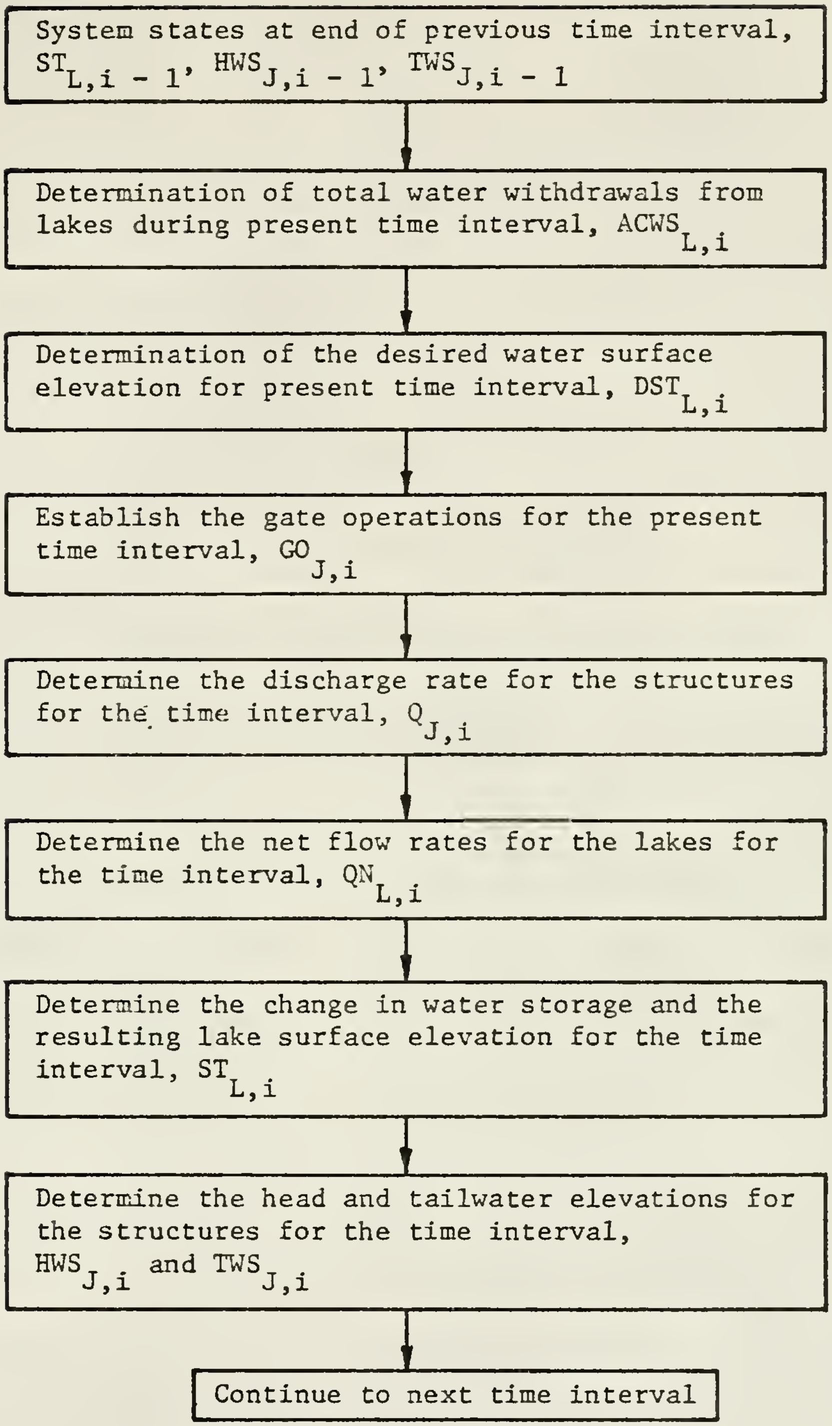
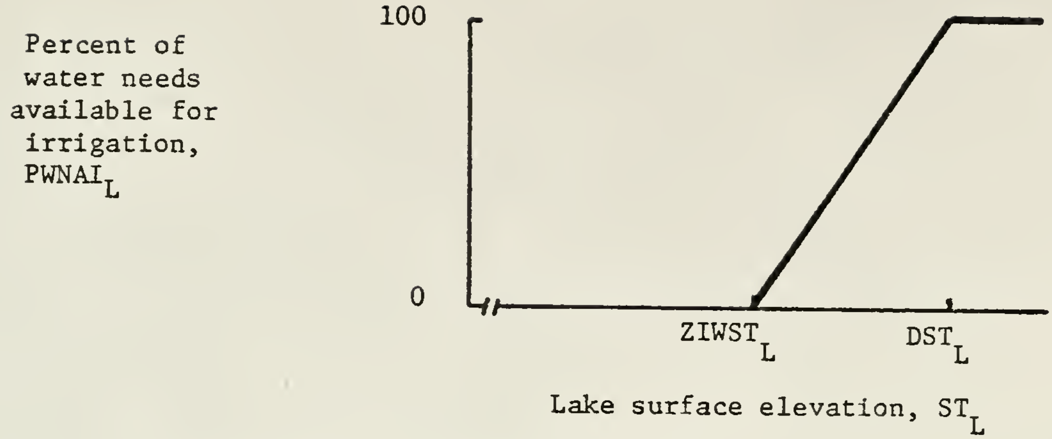
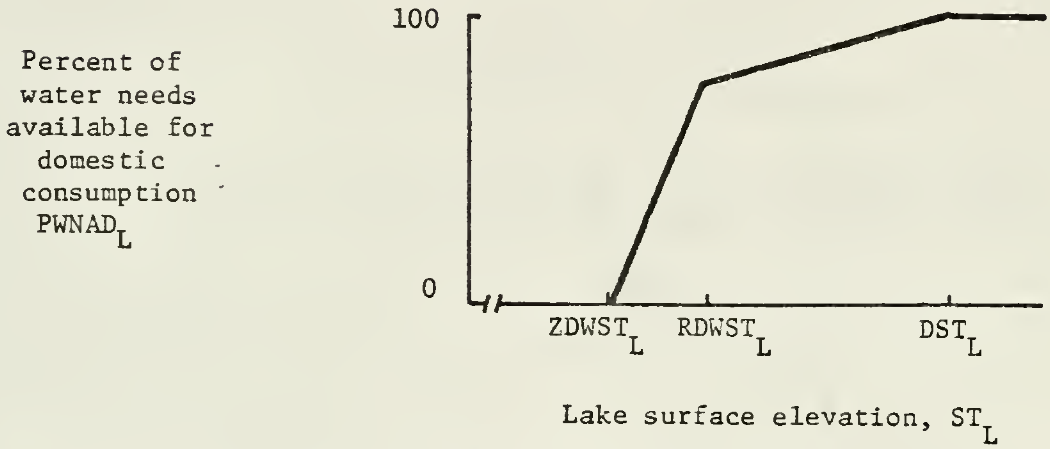


Figure 8. Sequence of calculations in the water surface elevation management model.



(a) Irrigation withdrawal function



(b) Domestic consumption function

Figure 9. Consumptive withdrawal function.

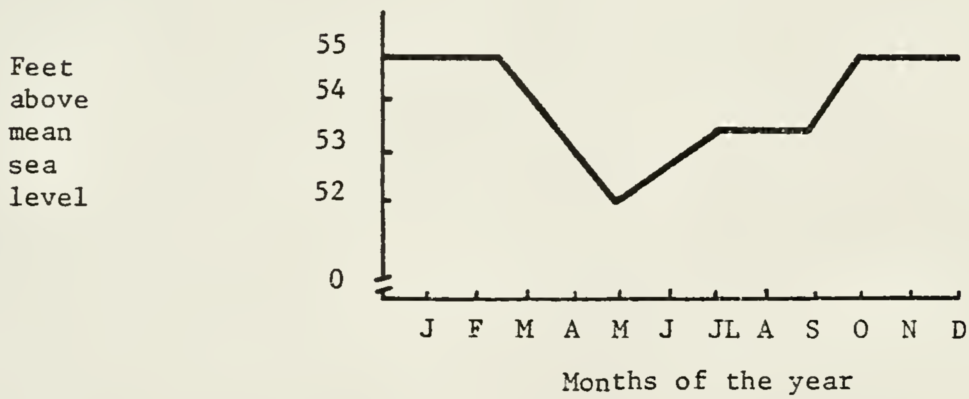
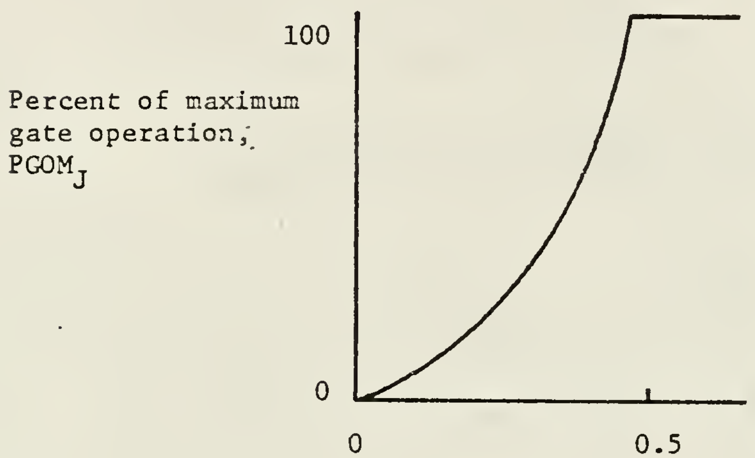


Figure 10. A typical regulation schedule.

lake regulation schedule or rule curve. A typical one, in this case for Lake Tohopekaliga, is shown in Figure 10. The gate operation, the number of feet a given gate is opened, is a function of the difference between the actual lake level at the end of the previous time interval and the desired lake level for the present interval, and is specified by DDA_L. The function used is illustrated in Figure 11. The percent of the maximum gate operation is determined and multiplied times the maximum gate opening.



$PGOM_J = 0, \; DDA_L \leq 0$

$PGOM_J = 400 * (DDA_L)^2,$

$0 \quad DDA_L \quad 0.5$

$PGOM_J = 100, \; 0.5 \leq DDA_L$

Difference between actual lake level and desired lake level, DDA_L, in feet

Figure 11. The gate operation function.

The flow rate through a given structure during the time interval can be obtained from the gate operation and the effective head across the structure. It is assumed the difference between the headwater elevation and the tailwater elevation at the end of the previous time interval represents the effective head during the present interval. That is,

$$EH_{J,i} = HWS_{J,i-1} - TWS_{J,i-1}1.$$

flow through the gate-type structures is given by

$$Q_{J,i} = P_J \ (GO_{J,i})^{r_J} \ \ (EH_{J,i})^{s_J}$$

where p_J, r_J, and s_J are regression-determined characteristic coefficients for the individual structures.

With these values the net flow rates for each of the lakes during the time interval can be found. And this, along with the stored water, is used to determine the lake surface elevation at the end of the present time interval. The set of lake surface elevations is the basic input into the water use models.

Headwater and tailwater elevations occurring at the end of the present time interval must be calculated as they are needed for determining the effective head in the next time interval. In the study, two situations occur. These are illustrated by using East Lake Tohopekaliga and Lake Tohopekaliga schematically in Figure 12. In the first case structure 4 has a canal, 7, leading to it and one, 8, leading from it. When structure 4 is open, the headwater elevation for it will be different from the water surface elevation for lake 4. Likewise the tailwater elevation will differ from the water surface elevation for lake 5.

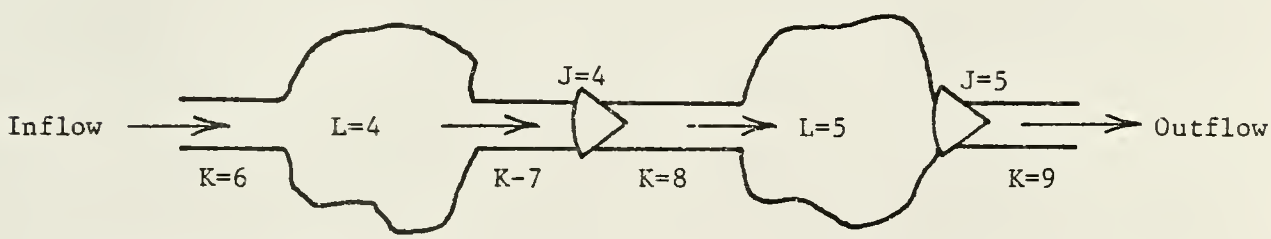


Figure 12. Schematic diagram of the lake, canal, and control structure relationship.

The second case has the structure at the lake exit so there is no upstream canal. The headwater elevation for structure 5 will be the same as the water surface elevation for lake 5. The tailwater elevation will be different from the downstream lake.

A technique developed by Prasad [19] and suggested by Sinha [21] was used to compute the water surface profile along the canals. A change in water surface elevation, WSE, with respect to space can be represented by,

$$\frac{d(WSE)}{dx} = \frac{dB}{dx} + \frac{dy}{dx} \qquad \text{where } B = C + z.$$

Integrating we get:

$$WSE = B + y = C + z + y$$

where

WSE = water surface elevation,

B = stream bed elevation from mean sea level at upstream point of the reach,

c = stream bed elevation from mean sea level at downstream point of the reach,

x = distance along the stream bed,

z = change in bed elevation between upstream point and downstream point of the reach, and

y = depth of water.

The differential equation of gradually varied flow provides the relationship between water depth and distance and can be expressed:

$$\frac{dy}{dx} \quad \frac{SO - SE}{1 - \frac{\alpha Q^2 T}{gA^3}}$$

where

SO = slope along the stream bed

SE = energy gradient

α = velocity head coefficient

Q = discharge through a given control structure,

T = top width of the channel cross-section,

g = acceleration due to gravity, and

A = cross-sectional area of the channel.

Manning's formula can be used for energy gradient.

$$SE = \frac{(RN)^2 V^2}{2.22 (HR)^{4/3}}$$

or substituting

$$V + \frac{Q}{A} \quad \text{and} \quad HR = \frac{A}{P}$$

$$SE = \frac{(RN)^2 Q^2 P^{4/3}}{2.22 A^{10/3}}$$

where

V = velocity of flow,

RN = Manning's roughness coefficient,

HR = hydraulic radius, and

P = wetted perimeter.

Substituting the energy gradient expression into the gradually varied flow equation, the result is:

$$\frac{dy}{dx} = \frac{SO - \dfrac{(RN)^2 Q^2 P^{4/3}}{2.22A^{10/3}}}{1 - \dfrac{Q^2 T}{gA^3}} .$$

This differential equation is a nonlinear function of y and is not readily solved analytically. Prasad [19] has developed a digital algorithm for solving the equation. The technique readily handles non-uniform channels and allows water surface profiles to be computed moving upstream or downstream.

Headwater elevations are thus found by starting at the lake outlet where the water surface elevation is the same as the lake surface elevation, or

$$WSE = ST_L.$$

The water surface profile is then determined by moving downstream to the structure. The intersection of the water surface profile and the structure gives the headwater elevation, $HWS_{J,i}$. The tailwater elevation, $TWS_{J,i}$, is found in a like manner except the profile is calculated moving upstream from the lower lake. The headwater and tailwater elevations at the end of the present time interval are now available for use in determining the flow rate through the structure during the next time interval.

The time interval used in this portion of the simulation is six hours in length. The sub-basin runoff values are aggregated to six hours. The results from the water surface elevation management model are, therefore, lake surface elevations for all lakes every six hours.

The institutional constraint model is not a distinct entity as are the other models but is a series of constraint functions incorporated in the others. The institutionally established regulation schedules for the lakes (see Figure 9) are built into the water surface elevation model. Each specifies the lake surface elevation for every day of the year. The schedule in this way reflects attitudes of society, through the FCD, as to how water in the lakes should be managed. Attitudes about the discharge

or export of water from a basin to another area are handled likewise. Minimum flows through outlet structures are handled in the water surface model thus satisfying the institutionally established water export requirements. The water withdrawal functions (see Figure 10) are built into the water use activities models in a similar manner. They indicate how the water should be allocated when the water availability is at certain levels. Society's attitudes about distribution of a scarce water supply are again reflected through the FCD.

Water Use Activities Models

The present study assumes four economic activities related to surface water. The net benefits accruing to these for spatial and temporal control of water are the primary indices of the management system's performance. Crop irrigation and domestic water supply are consumptive uses while recreation simply uses stored water. Property flooding is a result of excess surface water. All of these are functions of the amount of water in storage. The two consumptive uses gain more when larger quantities of water are conserved. The potential for flood damages increases with greater quantities of stored water and decreases with lesser quantities. Recreational use is only influenced at the extreme high and low water levels. Therefore, management of the system is primarily a trade-off between consumptive uses and flood control. This section of the study considers the determination of the benefits accruing to each of the activities from a given management procedure.

Surface water available for irrigation is a function of the amount of water available, and, as mentioned above, the function is institutionally

established. With the lake levels known, the percentage of the irrigation water needs that can be furnished can be determined. During the growing season the water needs for a crop are based on the irrigation water required to bring the soil to field capacity. Irrigation water is not applied until the soil moisture is depleted to one-third of the soil moisture available between the permanent wilting point and field capacity. When rainfall is applied the total moisture available to the crops during a given time interval is the sum of the moisture at the end of the previous time period, SMA_{i-1}, and the water entering the soil profile from irrigation, $WESI_i$, and rainfall, $WESR_i$.

Plant water use is based on the evapotranspiration equation proposed by Blaney and Criddle [3]. A modified form proposed by Phelcn [18] was used to estimate monthly potential evapotranspiration rates. It is given by

$$ET_p = k_c k_t \frac{T_a P_d}{100}$$

where

ET_p = monthly potential evapotranspiration rate in inches of water,

k_c = monthly crop coefficient which is a function of physiology and stage of growth of the crop,

k_t = temperature coefficient which is given by

$$k_t = 0.0173\ T_a - 0.314,$$

T_a = mean monthly temperature in °F, and

P_d = monthly percentage of daylight hours of the year.

The potential evapotranspiration for a given time interval is obtained by dividing the monthly potential evapotranspiration by the number of time intervals in the month. The actual evapotranspiration occurring is assumed to be a function of soil moisture. Studies at the United States Salinity Laboratory in California [8] indicate transpiration occurs at the full potential rate until a critical point in the available soil moisture is reached; thereafter the actual evapotranspiration lags the potential. Figure 13 illustrates the function used to obtain the proportion of the potential that gives the actual evapotranspiration

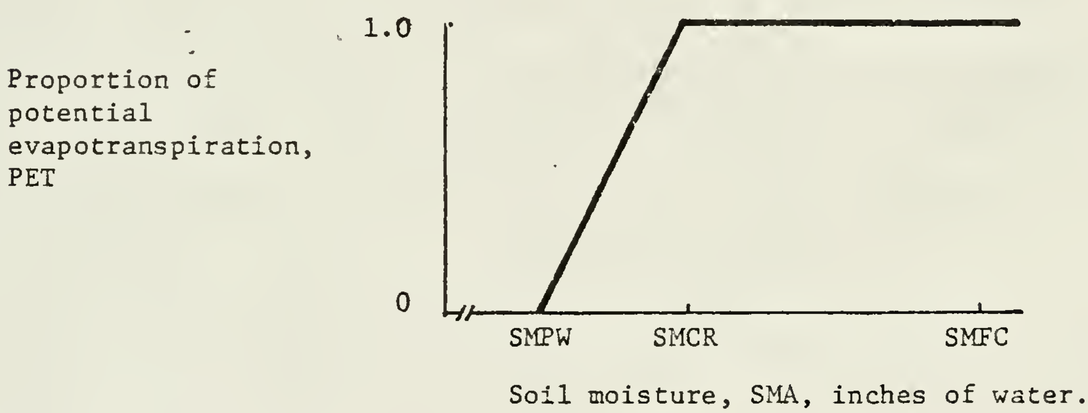


Figure 13. Potential evapotranspiration function.

in a given time interval. Therefore

$$AET_i = ET_{p,i}, \quad SMCR \leq SMA_i$$

$$AET_i = PET \; ET_{p,i}, \quad SMPW < SMA_i < SMCR$$

$$AET_i = 0, \quad SMA \leq SMPW$$

where

$ET_{p,i}$ = potential evapotranspiration during time interval i,

AET_i = actual evapotranspiration during time interval i,

PET = percent of potential evapotranspiration actually occurring,

SMA_i = soil moisture during time interval i,

SMFC = soil moisture at field capacity,

SMPW = soil moisture at permanent wilting point, and

SMCR = soil moisture at critical point.

The soil profile moisture at the end of a time interval is

$$SMA_i = SMA_{i-1} + WESI_i + WESR_i - AET_i.$$

It was assumed deep percolation occurs only when available soil moisture is at its capacity level. The soil moisture is used in the next time period to determine whether irrigation water will be applied and the rate at which evapotranspiration will occur.

The actual evapotranspiration occurring during each time interval is accumulated through the entire growing season to obtain the total water used by the crop. This is done for each crop, first, with both rainfall and irrigation water as the total water available and, second, with just rainfall as the total water available. At the end of the growing season there are two effective water inputs for each crop, ET_{total}, the actual total evapotranspiration when irrigation as well as rainfall is available, and ET_{rain}, the actual total evapotranspiration when only rainfall is used.

The availability of effective water on crop yields can be translated into benefits accruing to the users of water and used along with the benefits accruing to other uses of water as an index of water management effectiveness. To do this, the concept of producer surplus will be used, and the surplus is assumed to be the benefits accruing to society as a result of irrigation water being available. The producer surplus

is readily demonstrated by using traditional neoclassical production theory and assuming perfect competition in all markets. First, a crop production function is used which translates available effective water to crop yields when all other production factors are held constant. The traditional idealized production function is, implicitly,

$$\text{YIELD} = y(\text{ET, all other factors held constant})$$

and is illustrated along with the marginal physical product curve, MPP, and the average physical product curve, APP, in Figure 14. The crop yields with and without irrigation water, $\text{YIELD}_{\text{total}}$ and $\text{YIELD}_{\text{rain}}$, respectively, are obtained by solving the production function with ET_{total} and ET_{rain}, respectively. Multiplying the marginal physical product by the price of the crop, P_y, the marginal value product, MVP, is obtained. Mathematically,

$$MPP = \frac{\partial(TP)}{\partial(ET)},$$

$$MVP = P_y \frac{(TP)}{(ET)},$$

and, graphically, Figure 15. The price of the crop is assumed to be independent of activities in the river basin and constant, and is therefore the marginal revenue. First, substituting ET_{total}, and integrating, the total revenue for the irrigated crop, TR_{total}, is obtained,

$$\text{TR}_{\text{total}} = \int_0^{\text{ET}_{\text{total}}} P_y \frac{\partial(TP)}{\partial(ET)} \, d(ET),$$

Figure 14. Typical production, average physical product, and marginal physical product curves.

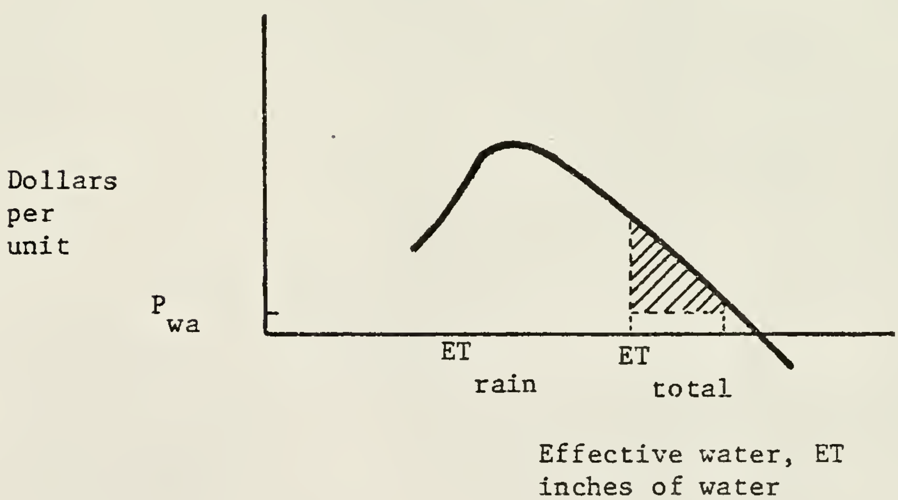


Figure 15. Typical marginal value product curve.

doing likewise with ET_{rain}, the total revenue for the crop without irrigation water, TR_{rain}, is obtained,

$$TR_{rain} = \int_0^{ER_{rain}} P_y \frac{\partial(TP)}{\partial(ET)} \, d(ET).$$

The producer surplus, PS, for each of these cases is the total revenue minus the price times the quantity. In the case of rainfall, no price was paid so the total revenue due to the effective water is the producer surplus. In the case of rainfall and irrigation, there is a price paid for just the irrigation water, so

$$P_w = 0, \quad 0 \leq ET \leq ET_{rain}$$

and

$$P_w = P_{wa}, \quad ET_{rain} \leq ET \leq ET_{total}$$

where

P_w = price of water, and

P_{wa} = price of irrigation water actually paid.

The producer surplus for this case is

$$PS_{total} = TR_{total} - P_{wa} (ET_{total} - ET_{rain}).$$

This is the producer surplus accruing to all the effective water without regard to its source. Only the irrigation water is available as a result of the water management system. Therefore, only the producer surplus

associated with the irrigation water is an appropriate indication of benefits due to the system management. The producer surplus for effective water from rainfall is subtracted from the producer surplus for the total effective water. Mathematically, this is

$$PS = \int_0^{ET_{total}} P_y \frac{\partial(TP)}{\partial(ET)} d(ET) - P \quad (ET_{total} - ET_{rain})$$

$$- \int_0^{ET_{rain}} P_y \frac{\partial(TP)}{\partial(ET)} d(ET)$$

and graphically, the shaded area in Figure 15.

The present study considered two crops, irrigated pasture and citrus. Irrigation water is assumed to be available in only sub-basins in which lakes are located. The growing season is the entire year, so actual evapotranspiration is determined daily and accumulated for the entire year. The management of water in each lake causes the available water to vary so that the actual evapotranspiration varies. The resulting producer surplus for each crop provides the benefits due to irrigation water being available for each crop grown near each of the lakes.

Surface water available for residential consumption is a function of the amount of water stored, and, as mentioned above, the function is institutionally established. The amount of water that can be removed from a lake is given as a percentage of the water needed. To obtain the maximum amount of water needed, an average consumer is assumed and his needs determined. Howe and Linaweaver [11] in an extensive study have formulated residential water demand models and estimated the relevant parameters from cross-sectional data. Their equation for total

residential demand was used and is

$$q_s = 86.3\ v^{0.474}\ (w_s - 0.6r_s)^{0.626}\ p_a^{-0.405}$$

where

q_a = average annual quantity demanded for domestic purposes in gallons per dwelling unit per day,

v = market value of the dwelling unit in thousands of dollars,

$(w_s - 0.6r_s)$ = lawn irrigation water needs in inches of water, and

p_a = the sum of water and sewer charges that vary with water use, evaluated at the block rate applicable to the average domestic use in cents per thousand gallons.

The average market value of the dwellings in the Kissimmee Basin, the average irrigation water needs for lawn grass, and total water price at the block rate applicable to the average domestic use were used in this equation to obtain the maximum daily water desired by each dwelling, WCPD. The actual daily water provided from surface water, GPD, is the product of this desired quantity and the percent of needs allowed. The balance of water the consumer demands, WCPD - GPD, is obtained from ground water.

The consumer surplus for domestic water consumption is assumed to be the benefits accruing to the water for residential use. The total residential water demand equation above is assumed to represent the demand for water up to a specific price, PRIU. At this point the demand function becomes perfectly elastic and is therefore a horizontal line to the origin (See Figure 16). It is assumed that at this price other sources of water become feasible. The consumer surplus for residential

use is

$$CSURP = \int_{PRIL}^{PRIU} q_a(p_a)\, dp_a - (PRIL \quad WCPD).$$

The portion of consumer surplus gained from surface water is

$$\int_{PRIL}^{PRIU} q_a(p_a)\, dp_a - \int_{PRIL}^{PRIW} q_a(p_a)\, dp_a + (PRIW - PRIL)\ GPD$$

or simply

$$\int_{PRIW}^{PRIU} q_a(p_a)\, dp_a + (PRIW - PRIL)\ GPD,$$

where

CSURP = the consumer surplus for residential use of surface water in cents,

$q_a(p_a)$ = the demand function for residential water,

p_a = price of residential water,

PRIU = highest price consumers will pay for water, in cents per thousand gallons,

PRIW = price consumers would pay for the actual quantity of surface water they received, in cents per thousand gallons,

PRIL = the price the consumer must actually pay for water, in cents per thousand gallons, and

GPD = quantity of surface water actually received in gallons per day.

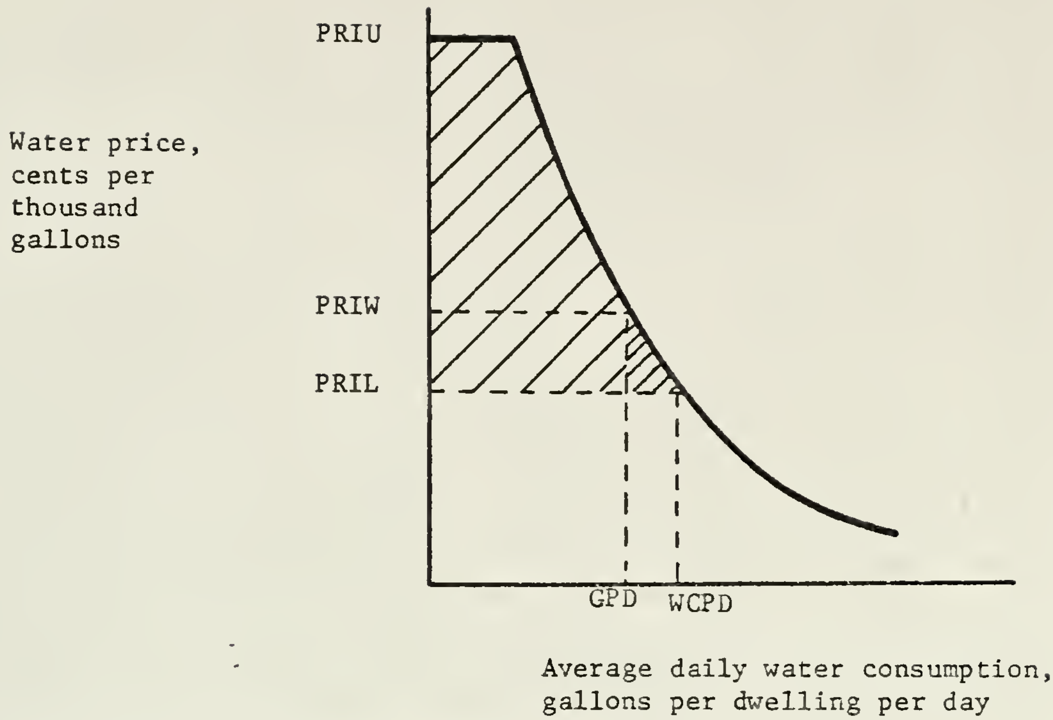


Figure 16. Residential water demand function.

The shaded area of Figure 16 illustrates the consumer surplus for all residential water, and the lightly shaded area is the consumer surplus for surface water. Or, the consumer surplus for surface water is the benefits accruing to the availability of surface water for residential use. The actual quantity of water used by residents from each lake is determined daily, and these quantities accumulated for the entire year. This quantity is then used to calculate the consumer surplus for the yearly consumption of surface water from each lake.

The lakes of the basin are used extensively for recreation, and the level of use is influenced by the depth of water. This is true because the lakes are quite shallow, and several feet of fluctuation drastically affects boating. When the water surface elevation is low,

large areas of the bottom are covered with only a foot or two of water, and, when the lake surface is high, access is limited and boat launching is difficult. Therefore, recreational use is assumed to be a function of water surface elevation as illustrated in Figure 17. Implicitly this may be written [2]

$$V = v(W_L, T, D_2, R_d, W_V),$$

where

V = number of visitors to lake per day,

W_L = lake surface elevation in feet above MSL,

T = daily temperature in °F

W_v = highest daily wind velocity in mph,

R_d = number of days of rain, and

D_2 = season of the year.

If this is assumed to be similar to a production function, the first partial derivation with respect to water level can be taken and considered as a marginal physical product. That is,

$$MPP_r = \frac{\partial V}{\partial W_L},$$

and the marginal value product is

$$MVP_r = P_v \frac{\partial V}{\partial W_L}.$$

The price of a visit, P_v, is assumed to be independent of the number of visits and is used as the marginal revenue of a visit. Benefits to recreational use of water can then be written

$$\int_{W_{L_m}}^{W_{L_o}} P_v \frac{\partial V}{\partial W_L} \, dW_L$$

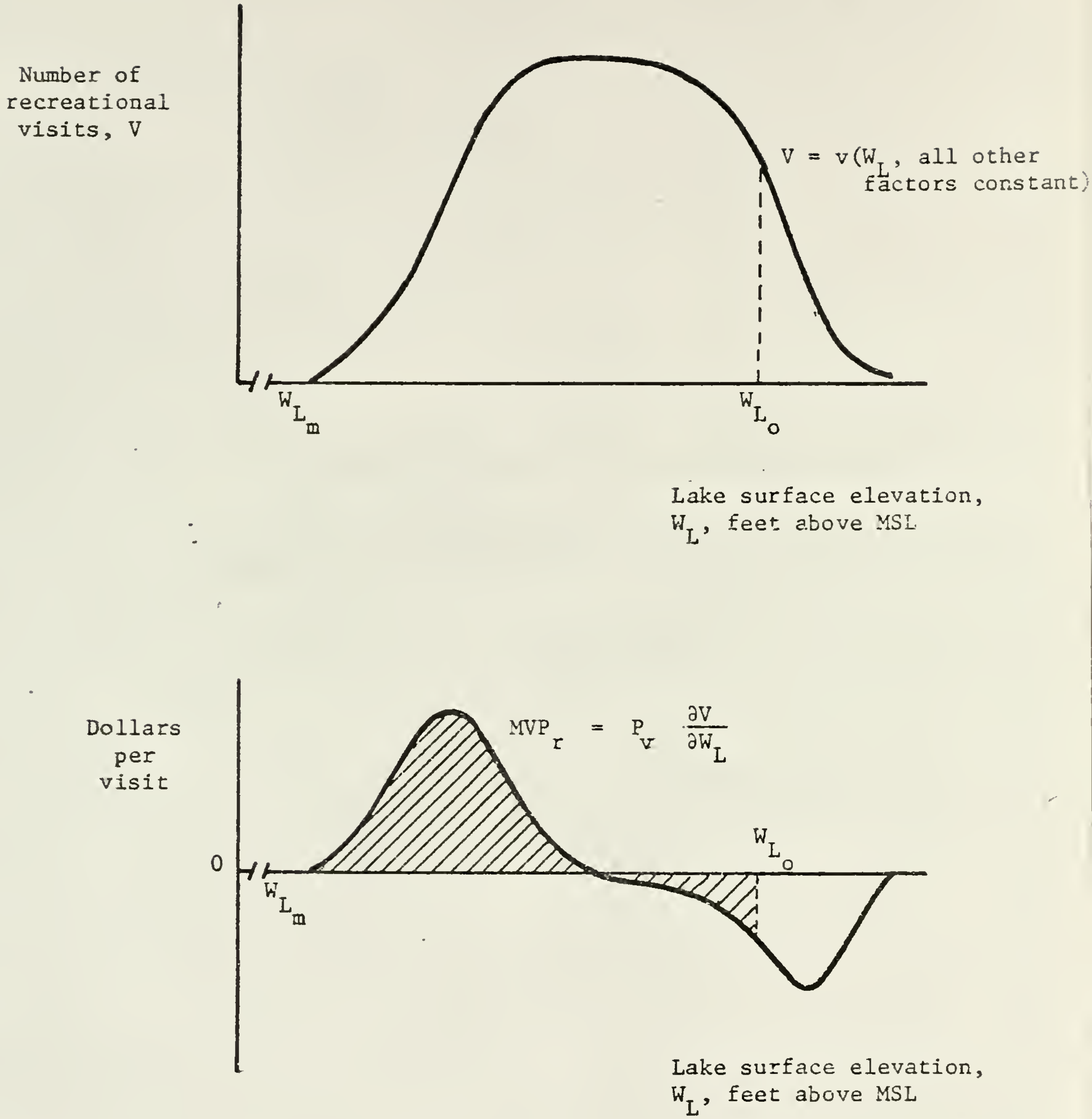


Figure 17. Recreational visit functions.

where

W_{L_o} = the actual lake surface elevation, and

W_{L_m} = the elevation of the bottom of the lake in feet above MSL.

There is no price for water level management; therefore, the benefits are the entire area under the marginal value product curve. It should be noted that the water surface elevation may be at any level and that recreational visits will be made. That is, limiting consideration to Stage II of the production function is no longer correct. This results in the situation shown in Figure 17, where the water surface elevation is above the point of highest use. The benefits accruing to this water level are shown by the shaded area above the axis minus the shaded area below.

The value of a visit, P_v, is not readily attainable, because there is no true market for recreational visits to the lakes of the Kissimmee Basin. McGuire [15] has estimated a demand function for recreation on these lakes by an average individual, D_r. In doing this, he assumed that the average individual's demand for recreation on the lake is not affected by the lake level. Some marginal users stop using the lake, but the average individual's demand remains the same. Since this is the case, the consumer surplus for an average individual making an average visit remains constant for varying water levels. Figure 18 illustrates this. Here $\bar{q}$ is the average length of stay per visit, $\bar{p}$ is the corresponding price, and p* is the highest price the average visitor will pay. The consumer surplus is

$$\int_{\bar{p}}^{p^*} D_r \, dp$$

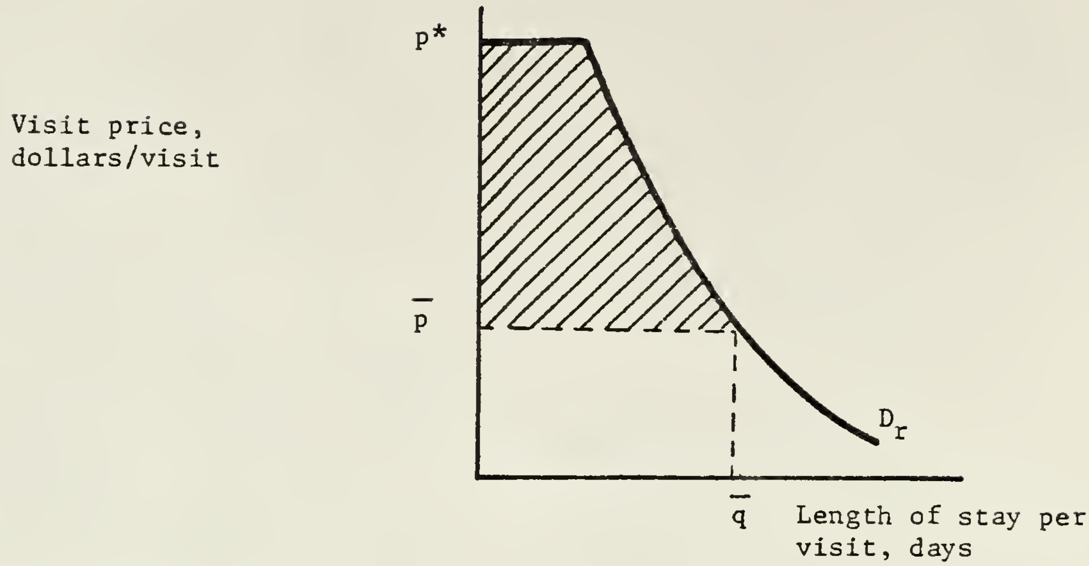


Figure 18. Recreation demand function.

and is illustrated by the shaded area in Figure 18. The value of a visit to be used in the benefit function is the consumer surplus for an average individual making an average visit to the lake.

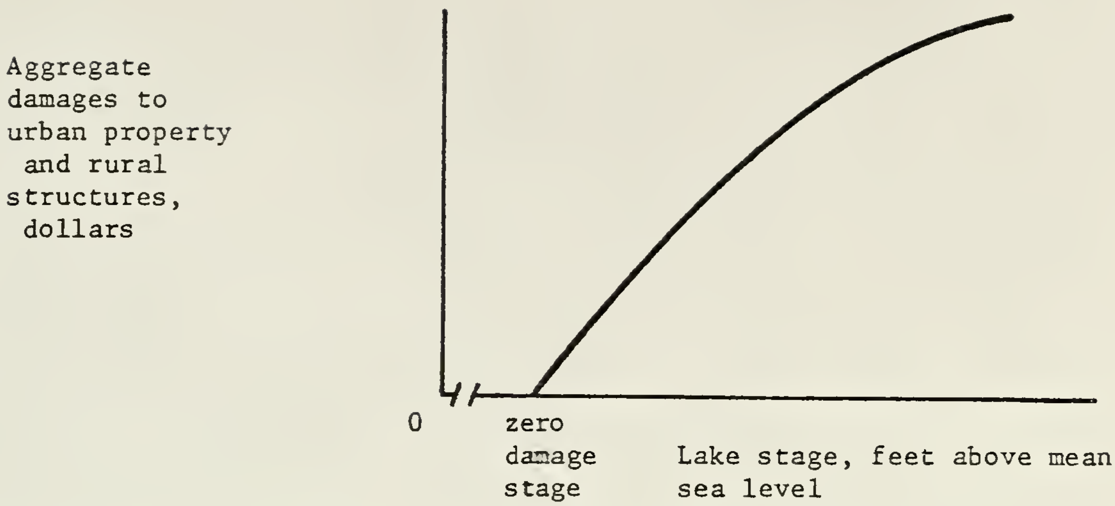
Benefits are higher in the first three water use activities when greater quantities of water are conserved. But, in the case of flood prevention, the lower the lake surface elevation and conserved water, the lower the probability of floods occurring. The higher the level, the higher the probability of flooding and the resulting flood damages. So, when flood protection becomes a concern in lake water management, there are conflicting operational objectives. The stochastic nature of rainfall aggravates the situation and makes the finding of a reasonably balanced operational policy difficult.

Flood damages are a function of the lake level and the activities at various elevations. In the case of agricultural crops, the duration of the flood is also a factor. Damage to crops increases with the time

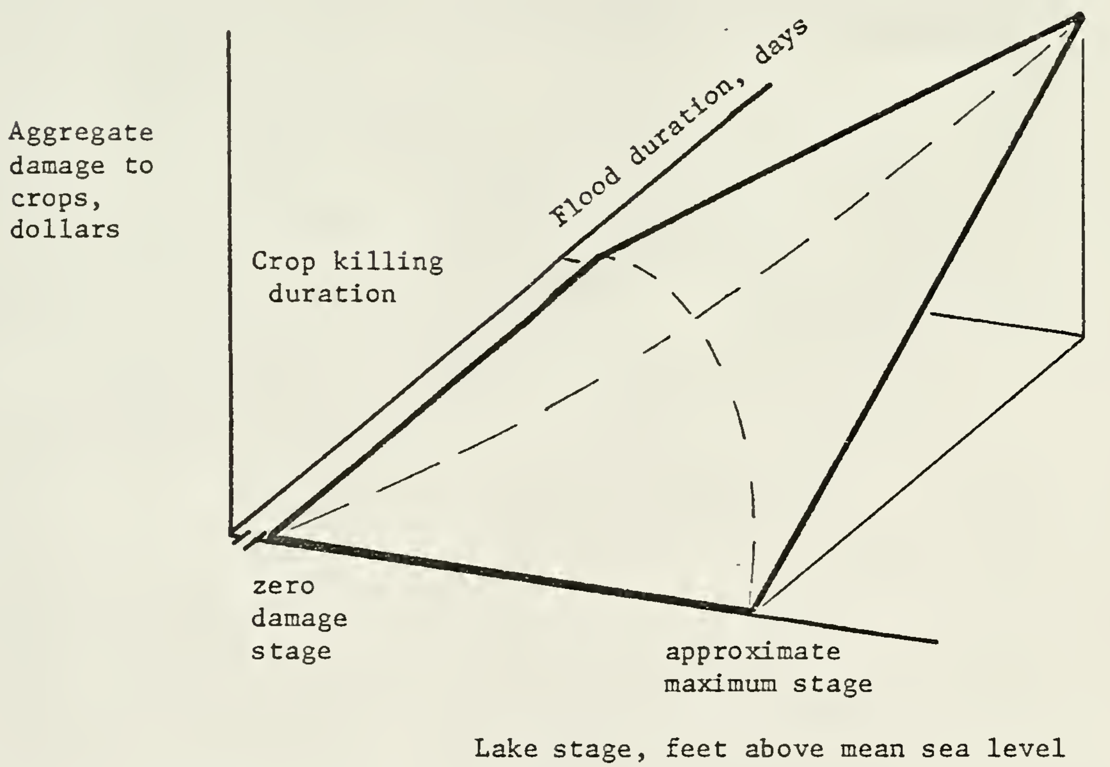
of exposure to saturated soil conditions until finally the crop is killed. The tolerance of crops to wet conditions varies; some crops can survive adverse conditions for long periods. Urban property and rural structures are considered to be damaged immediately; duration of flooding is not a factor. Momentary wetting of structures and machinery causes maximum damages.

The lack of demand functions for flood protection makes it impossible to use the surplus concept to determine benefits as was used for the other water use activities. The only avenue open for placing an economic value on the flooding phenomenon is to use the market value of replacing the damaged property. Lost net revenue to productive activities should also be considered. Flood damages resulting from lake water management policy are thus considered negative benefits.

Water surface elevations in the lakes are available every six hours from the water management model, making it possible to monitor all floods occuring. Urban and structure damage is determined by entering the maximum flood stage in an aggregate damage function. In the present study a simple linear segmented expression is used. It is assumed that thirty days are required to repair urban and rural structure damages, so property previously damaged cannot be redamaged until thirty days has elapsed. Figure 19a illustrates the function for a typical lake. Crop damages are obtained by determining the mean flood stage during the duration of the flood. These, the mean stage and length of flood, are entered in a crop aggregate damage function. Figure 19b illustrates such a function for a given crop growing adjacent to a given lake.



(a) An urban property and rural structures damage function.



(b) A crop damage function.

Figure 19. Flood damage functions for a typical lake.

Policy Evaluation Capabilities of the Model

Simulation models, by their very nature, allow easy modification of function specification. This provides a ready means of considering policy changes and the resulting effect on the overall management system. The proposed changes, however, must come from an understanding of the nature of the management and not a haphazard altering of variables and functions. The suggested policy changes will come from the technical staff after thorough study of the problems facing the water management authority.

The simulation model can readily handle investigations of policy concerned with spatial and temporal allocation of surface water as well as changes in surface water demand by specific economic activities. The water stored in the system of lakes is a function of the management of the control gates. The actual day-to-day operation of the gates is specified by the regulation schedules or rule curves for each structure. These rule curves are the long-term management policy. Briefly, they indicate that on a given day the water surface elevation of a given lake should be at a certain level. The schedule is given for an entire year. It is by varying the shape of these rule curves that alternative spatial and temporal allocations can be considered. In this case, the information flow in Figure 4 is from the long-term surface regulation policy box into the gate operation model.

A typical investigative simulation would be as follows: Basin input into the water management sub-model is a generated set of sub-basin runoffs from the rainfall and streamflow sub-models. The gate openings during the run are determined by the specified rule curves. The

resulting set of lake states is submitted to the economic activities model, and the net benefits accruing to this management procedure determined. The run would be made over a sufficient period of time to allow the stochastic character of the hydrology to be reflected in the sets of lake states and benefit states. Alternative regulation schedules would be examined in a similar manner using the same input data set.

Variation of the regulation schedules for structures within the basin allows study of spatial and temporal allocation within the study basin. In a similar manner, the effect of water exported from the basin on the benefits accruing to the basin can be investigated. To accomplish this, specific flow rates through the outlet structure are set, and the effect on the lakes determined.

The effects of land and water use changes on net benefits accruing to the basin can also be readily explored. Particular changes in land use, the resulting change in water demand, and the regulations allowing surface water withdrawal are considered. In the land use case the particular changes are entered by modifying the appropriate variables in the water use activities model. When the water withdrawal regulations are altered, the function changes are made in the institutional constraint model. In both cases, a set of runoff values is used, and a set of lake states determined. The net benefits to this set of states and water uses are calculated and provided an indication of the effects of the use changes.

The use of the simulation for each of these policy considerations and activity changes will be demonstrated. A complete study of each will not be performed, but, rather the type of information resulting from a study and used in the policy evaluation by the staff will be generated.

CHAPTER IV

BASIC DATA INPUTS TO THE MODEL

Many interesting simulation models can be conceptualized, but never materialize into useful tools. They are seen to have real potential in considering the complex interactions of water resource allocation problems, but often are not used because there are insufficient, low-cost data. A first attempt at modeling a system, however, can often be made with very limited data, and this can point out where more precise data are needed. A working model should be developed as early as possible.

In this present study some of the data are quite accurate, while others are only approximations. An early working model was desired, so the usefulness of an integrated approach could be demonstrated. The following describes the type of data and functions used in the working model.

Hydrologic Data

The hydrologic input is obtained from the FCD rainfall and streamflow models. These models were developed and put into operational form by the FCD [22, 23]. Rainfall can be either historic or synthetic, but for the present study, daily historic data collected from twelve gauging stations in the basin are used. The daily values are distributed in the twenty-four hours and over the fourteen sub-basins. The

distributed values in turn are translated into three-hour runoff quantities for the sub-basins. The FCD generates the three-hour runoff values for each of fourteen sub-basins and these provide the fundamental hydrologic input to the models constructed for the present study.

Water Management System Data

The water management model consists of a series of components describing the lakes, gate structures, and canals, and the manner in which they are used. Water surface elevation is a function of the quantity of stored water and the lake configuration. The relationships for the seven lakes are presented in Table 3, and were obtained using one foot-interval contour maps. The gate structure relationships were obtained empirically by the FCD, and are presented in Table 4. The canals, although actually having somewhat irregular bottom slopes and cross-sections, were assumed to have constant bottom slopes and uniform cross-sections throughout the length of each reach. Data providing cross-section characteristics at 200-foot intervals are available but would be expensive to use. The model for calculating the water surface elevations along the canal can easily accept these data if needed for greater accuracy. The characteristics used are presented in Table 5.

Surface water available for irrigation and domestic consumption is controlled by the FCD. Very little surface water is presently used for either of these activities, and this is managed through permits. When large quantities of surface water are needed in the future, the amount allowed will have to be controlled, so the present study suggests the amount be a function of lake surface elevations or available storage.

Table 3. Relationships between water storage levels and lake storage.

Lake Surface Elevations, ft. above mean sea level	Lake 1	2	3	4	5	6	7
	Storage in acre-feet						
42	1,050		72				64,000
43	1,105		111				81,000
44	1,160		160				103,800
45	1,955		226				130,530
46	2,750		318		8,000		179,030
47	3,390		444		17,000		217,630
48	4.025		653	24,900	26,000		259,700
49	4,745		955	33,400	40,500		306,100
50	5,478		1,381	42,400	55,300		357,300
51	6,400		1,989	51,900	69,000		414,100
52	7,365	165	2,890	61,800	84,000		475,900
53	9,482	602	4.032	71,800	101,200		541,800
54	12,659	1,137	5,151	82,700	122,600	5,600	625,200
55	15,010	1.679	6,520	94,200	144,200	6,700	727,900
56	17,970	2,436	8,105	106,000	170,500	8,000	851,200
57	21,387	3,296	9,827	118,300	194,700	9,300	986,000
58	25,296	4,286	11,739	130,000	222,600	10,800	1,181,500
59	29,545	5,446	14,000	143,700	250,000	12,300	
60	34,440	6,805	16,248	158,600	280,500	13,900	
61	39,518	8,077	17,480	176,400	306,000	15,500	
62	44,950	9,632	20,900	194,300	335,000	17,200	
63	50,555	11,421	23,940	210,500	360,000	20,000	
64	57,430	13,611	27,200	227,500	390,000	23,700	
65	66,966	16,456	33,400	250,000	420,000	29,000	
66	80,615					35,600	
67	98,434					42,000	
68	120,348					48,300	

Table 4. Gate structure characteristics.

Structure No.	Structure Type	Max. Gate Opening, ft.	Max. Discharge, cubic feet per second	Discharge Equation
1	Double culverts with gates	4.0	160	Submerged flow: $Q = 15.92\ F \left(\frac{EH}{0.03921\ F^2 + 0.0078}\right)^{1/2}$ for GO _ 1 ft., $P = 0.143\ (GO)^{1.14}$ for GO 1 ft., $P = 0.1828\ GO - 0.0398$ for P _ 0.5, $F = \frac{1}{\ }\ [\ - \arctan\left(\frac{\sqrt{p-p^2}}{1-2p}\right) - 2(1-2p)\sqrt{p-p^2}$ for P 0.5, $F = \frac{1}{\ }\ [\arctan\left(\frac{2\sqrt{p-p^2}}{1-2p}\right) - 2(1-2p)\sqrt{p-p^2}]$ Non submerged flow: $Q = 78\ (EH)^{0.495}$
2	Double culverts with gates	4.5	170	Same as structure no. 1

Continued

Table 4. Gate structure characteristics. (Continued)

Structure No.	Structure Type	Max. Gate Opening, ft.	Max. Discharge, cubic feet per second	Discharge Equations
3	Gate Structure	6.0	640	Submerged flow: $Q = 10.5\ GO\ [2g(EH)]^{1/2}$ Free controlled flow: $Q = 95.2\ (GO)^{0.956}\ (HWS - 55.3 - 0.5\ GO)^{0.353}$ Free uncontrolled flow: $Q = 85.5\ (HWS - 55.3)^{1.315}$
4	Gate Structure	8.9	820	$Q = 125.21\ (GO)^{1.10}\ (EH)^{0.255}$
5	Gate Structure	18.1	2,300	$Q = 122.6\ (GO)^{1.142}\ (EH)^{0.519}$
6	Gate Structure	9.2	450	$Q = 86.11\ (GO)^{1.156}\ (EH)^{0.2411}$
7	Gate Structure	7.8	715	$Q = 114.09\ (GO)^{1.1044}\ (EH)^{0.2108}$
8	2-gate Structure	11.1	2,000	$Q = 116.40\ (GO)^{1.1}\ (EH)^{0.24}$
9	3-gate Structure	13.2	11,000	$Q = 391.7998\ (GO)^{0.9630}\ (EH)^{0.466}$

Note: Q = water flow through a gate in cubic feet per minute; GO = gate operation in feet; EH = effective head across a gate in feet, and HWS = headwater elevation in feet above MSL.

Table 5. Canal characteristics.

Canal No.	Bottom Width, Ft.	Side Slope	Manning's Roughness Coefficient	Upper End Elevation, Ft. MSL	Bottom Slope	Length of Reach, Ft.
1	5	1/2	0.168	52.80	5.8×10^{-6}	4,751
2	5	1/2	0.168	51.50	5.8×10^{-6}	6,200
3	5	1/2	0.168	51.25	7.0×10^{-5}	7,245
4	5	1/2	0.168	49.90	1.21×10^{-4}	5,762
5	10	1/2	0.168	48.60	1.11×10^{-4}	898
6	10	1/2	0.168	47.00	1.43×10^{-4}	6,912
7	20	1/2	0.168	46.60	1.48×10^{-4}	2,425
8	20	1/2	0.168	45.00	1.26×10^{-4}	18,280
9	20	1/2	0.168	34.00	5.6×10^{-5}	23,200
10	10	1/2	0.168	53.45	2.47×10^{-4}	4,016
11	10	1/2	0.168	51.00	5.2×10^{-5}	9,602
12	40	1/2	0.168	46.70	4.22×10^{-4}	15,080
13	60	1/2	0.168	40.50	9.6×10^{-5}	15,461

The functions used are given in Figure 23 (see Chapter V). The actual shape of these will be varied to determine the effect of different consumptive withdrawal policies (see Figure 23, Chapter V).

Water Use Data

The irrigation simulation produces the crop yield possible with the water available and determines the net revenue for the crop. Surface water and rainfall provide the available water. Sixty percent of the rainfall and seventy percent of the applied irrigation water are assumed

to be available in the root zone. The evapotranspiration by the crop is utilized in a production function, and variations in this cause different crop yields. The maximum monthly evapotranspiration values for pasture grass and citrus in the Kissimmee Basin were obtained from the Soil Conservation Service and are presented in Table 6. The actual evapotranspiration is a function of soil moisture, and daily calculations of both are made. The moisture retention capacity of the soils is important, and the parameters for the sandy soil of the Kissimmee Basin, assumed to be predominantly Leon fine sand, are given in Table 7.

The crop yields and production costs were obtained from data collected by Conner and Reynolds.* For this first generation simulation simple linear production functions are used, and are assumed to approximate Stage II production with all other factors held constant. The source data showed costs were a function of crop yield as well as the amount of irrigation water applied, indicating all other factors were not actually constant. These were, however, the best data available at the time. Prices of all goods were assumed not to be affected by the activities in the basin. That is, perfect competition in all models was assumed. Since the production function is linear and prices perfectly elastic, the marginal value product line is horizontal, and the producer surplus for a crop with irrigation is

$$PS_{total,L} = P_y \ (YIELD_{total}) - COST_{total,L}$$

*J. R. Conner and J. E. Reynolds, personal communication.

Table 6. Evapotranspiration information.

Crop	Month	Avg. Temp., °F, T_a	% Daylight Hours P_d	Temperature Coefficient, k_t	Crop Coefficient, k_c	Potential Evapotranspiration ET_p
Pasture	Jan.	62.4	7.44	.76	.48	1.67
	Feb.	63.8	7.10	.79	.57	2.04
	Mar.	67.1	8.38	.85	.74	3.54
	Apr.	71.8	8.66	.93	.86	4.98
	May	76.8	9.41	1.02	.90	6.65
	Jun.	80.4	9.34	1.08	.92	7.43
	Jul.	81.7	9.53	1.10	.92	7.87
	Aug.	82.1	9.14	1.11	.91	7.58
	Sep.	80.6	8.32	1.08	.87	6.31
	Oct.	75.3	8.04	.99	.80	4.78
	Nov.	68.0	7.32	.86	.67	2.89
	Dec.	63.5	7.32	.78	.52	1.91
						57.65
Citrus	Jan.	62.2	7.40	.76	.63	2.20
	Feb.	63.8	7.07	.79	.66	2.35
	Mar.	67.3	8.37	.85	.68	3.25
	Apr.	72.0	8.67	.93	.70	4.06
	May	77.0	9.46	1.02	.71	5.27
	Jun.	80.6	9.39	1.08	.71	5.81
	Jul.	81.9	9.58	1.11	.71	6.19
	Aug.	82.2	9.17	1.11	.71	5.94
	Sep.	80.6	8.32	1.08	.70	5.07
	Oct.	75.1	8.02	.98	.69	4.07
	Nov.	67.8	7.28	.86	.67	2.85
	Dec.	63.2	7.27	.79	.64	2.30
						49.36

Note: These data were provided by the Soil Conservation Service, United States Department of Agriculture.

Table 7. Soil information.

Soil Characteristics	Crop Pasture	Crop Citrus
Field capacity (0.1 atm), inches of water per foot of soil	1.50	1.50
Permanent wilting point (15 atm) inches of water per foot of soil	0.55	0.55
Root zone, inches of soil	36.00	60.00
Available moisture at field capacity, SMFC, inches of water	4.50	7.50
Available moisture at permanent wilting point, SMPW, inches of water	1.65	2.75
Available moisture at point where ET begins to decrease, SMCR, inches of water	2.60	4.33

and without irrigation

$$PS_{rain,L} = P_y \ (YIELD_{rain,L}) - COST_{rain,L}.$$

The producer surplus indicating the level of benefits due to the availability of surface water from a given lake for irrigation is

$$PS_L = PS_{total,L} - PS_{rain,L}.$$

Table 8 gives the equations used for crop yields and production costs, as well as crop prices.

The calculation of consumer surplus for residential use of surface water requires the total amount of water an average household uses, WCPD. The quantity assumed for the Kissimmee River Basin is 13,500 gallons per

Table 8. Crop yields, production costs, and prices.

Crop Yield Functions

a. Beef yields in pounds/acre

$$YIELD_{B,L} = -200 + 14(ET_{B,L}), \quad 20 \le ET_{B,L} \le 70$$

b. Mixed citrus yields in boxes per acre

$$YIELD_{C,L} = -300 + 17(ET_{C,L}), \quad 20 \le ET_{C,L} \le 70$$

Cost Functions

a. Beef production costs in dollars per acre

$$COST_{B,L} = 8.76 + 0.1\ (YIELD_{B,L}) + 0.056(ET_{total,B,L,} - ET_{rain,B,L})$$

b. Citrus production costs

$$COST_{C,L} = 172.02 + 0.145(YIELD_{C,L}) + 2.40(ET_{total,C,L} - ET_{rain,C,L})$$

Crop Prices

a. Beef price in dollars per pound

$$PRI_B = 0.25^a$$

b. Mixed citrus price in dollars per 90 pound box

$$PRI_C = 1.40^a$$

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[a] Average prices for period 1968 through 1970.

month or WCPD is 370 gallons per day.* On the charge rate schedules for Kissimmee and St. Cloud, this quantity corresponds to a combined water and

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* This figure was obtained by questioning officials of the Kissimmee and St. Cloud utilities departments and is an estimate.

sewer charge of 60 cents per thousand gallons. The residential demand function becomes

$$q_a = 1930.669 \quad (p_a)^{-0.405}$$

when an average market value for dwellings of $20,000, and an average lawn irrigation requirement of fifteen inches per year are used.* Substitution of q_a = 370 gallons per day again gives a price of approximately 60 cents.

The proportion of daily water needs that can be removed from the lakes is specified by the institutionally established withdrawal functions. This proportion and the total water needs, WCPD, give the quantity of water removed from the lake, GPD_L. Substituting GPD_L into the demand equation gives $PRIW_L$. PRIU is set at 120 cents per thousand gallons, and PRIL is then above 60 cents per thousand gallons. With this information the consumer surplus for each dwelling can be calculated. Only lake 4 and 5 were assumed to have residents using surface water. Lake 4 had 1580 dwellings in the surrounding area and lake 5 had 4750. Using the consumer surplus on a lake, the benefits accruing to the use of surface water can be found.

Behar [2] has demonstrated the effect of water surface elevation on recreational visits to lakes in the Kissimmee Basin with his linear relationship for Lake Tohopekaliga. More specifically, he found a reduction of 25.63 visits per foot decrease in water level below the minimum desired level. This represents 11.5 percent of the 223.32 visits per day average, and implies for each foot of drop there is an 11.5 percent

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* Again, these are estimates obtained by informal questioning of various people in Kissimmee and St. Cloud.

drop in the number of visits. Or, in a range of 8.7 feet, there will be a 100 percent drop in visits. There are no data to support a decrease in visits for surface elevations above the minimum desired level, but it is reasonable to assume this is the case. Lake Tohopekaliga was assumed to be typical of the lakes in the basin, and Behar's 11.5 percent per foot of lake surface drop was used when the lake surfaces were below the desired level. A 20 percent decrease in visits per foot of water surface increase was used when the lake surface was above the desired level.

Functions of the type shown in Figure 20 are used. Values for the elevations for each lake are given in Table 9. Since the relationship between water surface elevations and number of visits is a linear segmented function, the pseudo-marginal product and the marginal value product curves are step functions. The benefit to recreational use of the lakes is found by simply multiplying the number of visits per month by the value of an average visit, in this case, the consumer surplus for an average visit.

The number of visits per month is found by entering the mean monthly water surface elevation for a given lake in the linear segmented function and obtaining the percent of maximum monthly visits, PRB_L. This percent is then multiplied times the maximum number of visits for that month, $NRECVM_L$. Behar's [2] data were used to estimate the number of recreation visits when the lakes were at the desired elevations (see Table 10).

Gibbs and Conner [9], using McGuire's [15] recreation demand function, estimated the consumer surplus, PCSURP, for an average individual making an average recreational visit to a basin lake to be

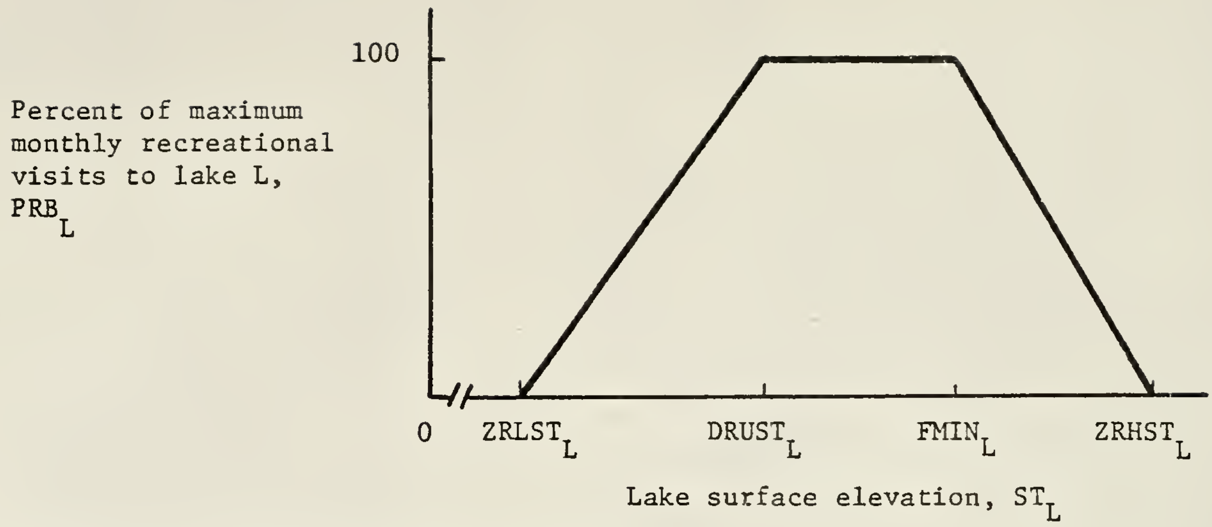

Figure 20. The recreational use function.

Table 9. Elevations for the percent of maximum monthly recreational visits functions.

L	$ZRLST_L$	$DRUST_L$	$FMIN_L$	$ZRHST_L$
1	53.28	62.0	64.5	69.5
2	51.28	60.0	62.5	67.5
3	50.28	59.0	61.5	66.5
4	47.28	56.0	58.5	63.5
5	44.28	53.0	55.5	60.0
6	51.28	60.0	62.0	67.0
7	40.28	49.0	53.0	58.0

Note: $ZRLST_L$ = the lower lake surface elevation at which there are no recreational visits; $DRUST_L$ = the lake surface elevation at which maximum recreational visits occur; $FMIN_L$ = the lake surface elevation at which the recreational visits begin to drop from the maximum; and $ZRHST_L$ = the higher lake surface elevation at which there are no recreational visits.

Table 10. Estimated monthly visits to each lake.

Lake	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1	1,984	1,369	1,369	1,369	1,369	388	387	387	388	1,682	1,683	1,985
2	110	153	153	153	152	71	71	71	72	126	126	109
3	1,600	721	721	720	720	663	664	664	664	892	893	1,600
4	5,433	4,450	4,450	4,450	4,450	2,085	2,085	2,085	2,085	6,257	6,258	5,434
5	5,886	10,872	10,872	10,871	10,871	8,652	8,652	8,652	8,652	8,121	8,120	5,886
6	1,419	272	272	271	271	81	81	81	81	824	825	1,420
7	17,610	13,351	13,351	13,351	13,350	13,395	13,395	13,394	13,394	16,159	16,160	17,611

\$58.88, the shaded area in Figure 18. This is based on an average visit, $\bar{q}$, of 5.64 days, an average price, $\bar{p}$, of \$3.23 per day, and a critical on-site cost, p*, of \$17.57. Using the consumer surplus and the number of visits to a particular lake during a month, the benefits accruing to the availability of surface water for recreation are found.

Flood damages for each of the lakes was found by investigating the activities at various elevations around the lake. The FCD gathered the data which were used to construct the functions. Urban and rural structure damages are expressed by the linear functions in Table 11. The land around the lakes slopes away from the lakes at a very flat angle and the area flooded increases linearly; therefore, linear functions provide a reasonable approximation. It is assumed that thirty days are required to repair damages, so property previously damaged cannot be redamaged until thirty days have elapsed.

Crop damages are a function of the mean flood stage and the duration of the flood. Again, the area flooded increases linearly, and if the crops are assumed to be uniformly distributed with respect to land elevation, a linear increase in damages associated with flood stage is reasonable. A hyperbolic paraboloid of the general form $z = cxy$, where c is a constant and x, y, and z are Cartesian coordinates, is used. This function has the property, that, when cut in the x-z or y-z plane, a straight line results. This allows a function to be obtained with very little data. This was convenient, since the FCD was only able to provide damage values for pasture and citrus when the crops were completely destroyed. This is identified as the killing flood duration, and was assumed to be fifteen days for pasture and five days for citrus. The functions obtained for each crop adjacent to each of the lakes are shown in Table 12.

Table 11. Urban and rural structures damage functions.

Lake	Urban	Rural Structures & Miscellaneous
1	$FUD_1 = 29,931,850 + 45,455\ ST_1$	$FRD_1 = -3,933,600 + 59,600\ ST_1$
2	$FUD_2 = 0$	$FRD_2 = 0$
3	$FUD_3 = 5,990,310 + 96,774\ ST_3$	$FRD_3 = 226,795 + 3,658\ ST_3$
4	$FUD_4 = 21,636,340 + 363,636\ ST_4$	$FRD_4 = -4,845,144 + 81,431\ ST_4$
5	$FUD_5 = 9,866,680 + 177,778\ ST_5$	$FRD_5 = -4,018,977 + 72,414\ ST_5$
6	$FUD_6 = 0$	$FRD_6 = -1,333,680 + 21,390\ ST_6$
7	$FUD_7 = -14,840,000 + 280,000\ ST_7$	$FRD_7 = 0$

Note: FUD_L = urban flood damages in dollars; FRD_L = rural structures and miscellaneous damages in dollars; and ST_L = lake surface elevation in feet above mean sea level.

Table 12. Crop damage functions.

Lake	Pasture	Citrus
1	$FPD_1 = 141(ST_1 - 64.5)\ DOF_1$	$FCD_1 = 5{,}455(ST_1 - 64.5)\ DOF_1$
2	$FPD_2 = 0(ST_2 - 62.5)\ DOF_2$	$FCD_2 = 0(ST_2 - 62.5)$
3	$FPD_3 = 524(ST_3 - 61.5)\ DOF_3$	$FCD_3 = 658(ST_3 - 61.5)\ DOF_3$
4	$FPD_4 = 452(ST_4 - 58.5)\ DOF_4$	$FCD_4 = 248(ST_4 - 58.5)\ DOF_4$
5	$FPD_5 = 587(ST_5 - 55.5)\ DOF_5$	$FCD_5 = 1{,}534(ST_5 - 55.5)\ DOF_5$
6	$FPD_6 = 434(ST_6 - 62.0)\ DOF_6$	$FCD_6 = 920(ST_6 - 62.0)\ DOF_6$
7	$FPD_7 = 2{,}750(ST_7 - 54.0)\ DOF_7$	$FCD_7 = 0(ST_7 - 54.0)\ DOF_7$

Note: FPD_L = pasture flood damages in dollars; FCD_L = citrus flood damages in dollars; ST_L = lake surface elevation in feet above mean sea level; DOF_L = duration of flood in days and has maximum values of 15 and 5 days for pasture and citrus respectively.

CHAPTER V

POLICY EVALUATION DEMONSTRATIONS

Policy evaluation capabilities of an organization can be expanded with simulation model use. The basis for the broadened capabilities lies in the ability to change formulations, parameters, and variables, while using the model as an apparatus to give insight into the complex interactions occurring in the real system. The simulation of the Kissimmee River Basin* is intended to demonstrate this usefulness in dealing with the difficult water management problems in south Florida. Demonstrations illustrating the potential of the model in four policy areas, (a) temporal and spatial water storage, (b) consumptive withdrawals, (c) minimum outflows, and (d) land and water use patterns, have been performed.

A simulation run can provide

1. The flow through each control structure along with the volume of water in storage and the water surface elevation for each lake at six-hour intervals.
2. The daily irrigation water applied, evapotranspiration, and soil moisture for each crop grown in the vicinity of each lake.
3. The crop yields and resulting irrigation dollar benefits for each crop grown around each lake.

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*The computer program written in Fortran IV and the complete set of data used in these demonstrations are available from the author or Mr. William V. Storch, Director, Department of Engineering, Central and Southern Florida Flood Control District, Box 1671, West Palm Beach, Florida 32402.

4. The daily quantity of water withdrawn from each lake for domestic consumption, and the resulting dollar benefits.
5. The monthly number of recreational visits and the accompanying benefits.
6. The floods and resulting damages to urban property, rural structures and individual crops occurring on each lake.

These data can be aggregated, used to calculate standard statistics, or put into any form useful in the staff and governing board evaluation. It should be noted that the dollar benefits can be used to compare the distributional effects of a policy as well as its overall economic efficiency. That is, the dollar benefits accruing to a particular water use associated with a particular lake can be obtained and compared to another use on another lake, and a policy selected on this comparison. Or, in the case of the efficiency criteria, a policy which produces the highest net benefits to the entire basin can be selected. The staff and governing board have a number of physical and economic indicators with which to compare policy alternatives.

Only a few of these indicators of policy performance are presented for the policy demonstrations discussed below. The availability of water for each water use activity, the floods occurring and certain aggregated dollar benefits are mentioned. The purpose of these was to give the reader a feel for the relative change in indicators when a change was made in certain parameter or formulation. The purpose was not to give an exhaustive study of each policy.

Two computers were used to perform the demonstrations. The rainfall and runoff calculations were performed on the FCD's CDC 3100

computer. The University of Florida's IBM 370, model 165 computer was used to run the water management model, the water use activities model, and the institutional constraint model. No cost figures were available on the operation of the rainfall and runoff models. The cost of running the other three models in the policy demonstrations was nine dollars for a one-year run.

Rainfall occurring over the basin during the period June 1, 1968 to May 31, 1971, was used as the basin input. A set of runoff values was generated using the FCD rainfall and streamflow models. This set of runoff values for the three years was used for each policy demonstration run.

This was an interesting time period because the first two years had typical rainfalls,while the third was very dry. The rainfall means for the fourteen sub-basins were approximately 53 inches and 57 inches for years 1 and 2, respectively. The third year mean was approximately 37.5 inches. This year was the beginning of the worst drought in the recorded history of south Florida. The results of this change of rainfall were seen in the policy demonstrations. For example, in simulation 1 using the present regulation schedule, group 1 crop acreages, and proportional withdrawal functions, recreation benefits dropped \$440,000, while irrigation benefits rose \$694,000 between year 1 and year 3.

Temporal and Spatial Water Storage

Temporal and spatial water storage is controlled by regulating the gates at the outlets of the lakes. The gates are opened and closed so as to maintain a certain lake elevation. The FCD specifies the lake

elevation for a given day with the lake regulation schedule. Ideally, the storage policy given by each of these will provide the maximum net benefits to the area. It is in the development of these schedules that the FCD will use the simulation model to study the effects of alternative storage policies.

The regulation schedules are best illustrated by linear segmented functions as shown in Figure 21. Here, each of the presently used schedules is shown. Generally, the lakes are allowed to reach a maximum elevation in the late fall, and then decrease through the winter and spring to a minimum at the beginning of the summer. This corresponds to the periods of light rainfall in winter and spring and heavy in the summer, although there is great variation.

Three configurations of regulation schedules were used in the demonstrations. The first consisted of three variations of the present regulation schedules. Simulation runs were made with (a) the present schedules for each lake, (b) the shape of the present schedules but with all elevations for a given day lowered one foot, and (c) the present schedules but with the maximum elevation raised one-half foot. The second configuration is a set of changes being proposed by the FCD. The proposed schedules for lakes 1, 2, 4, and 5 are given in Figure 22. The last configuration, constant lake elevations set at the highest elevation on the present schedules, is desired by many people with property fronting on the lakes [6].

Output from the model gives sufficient information to allow comparison of regulation schedules with respect to physical as well as economic states. Simulation 1 (see Table 13) using the present

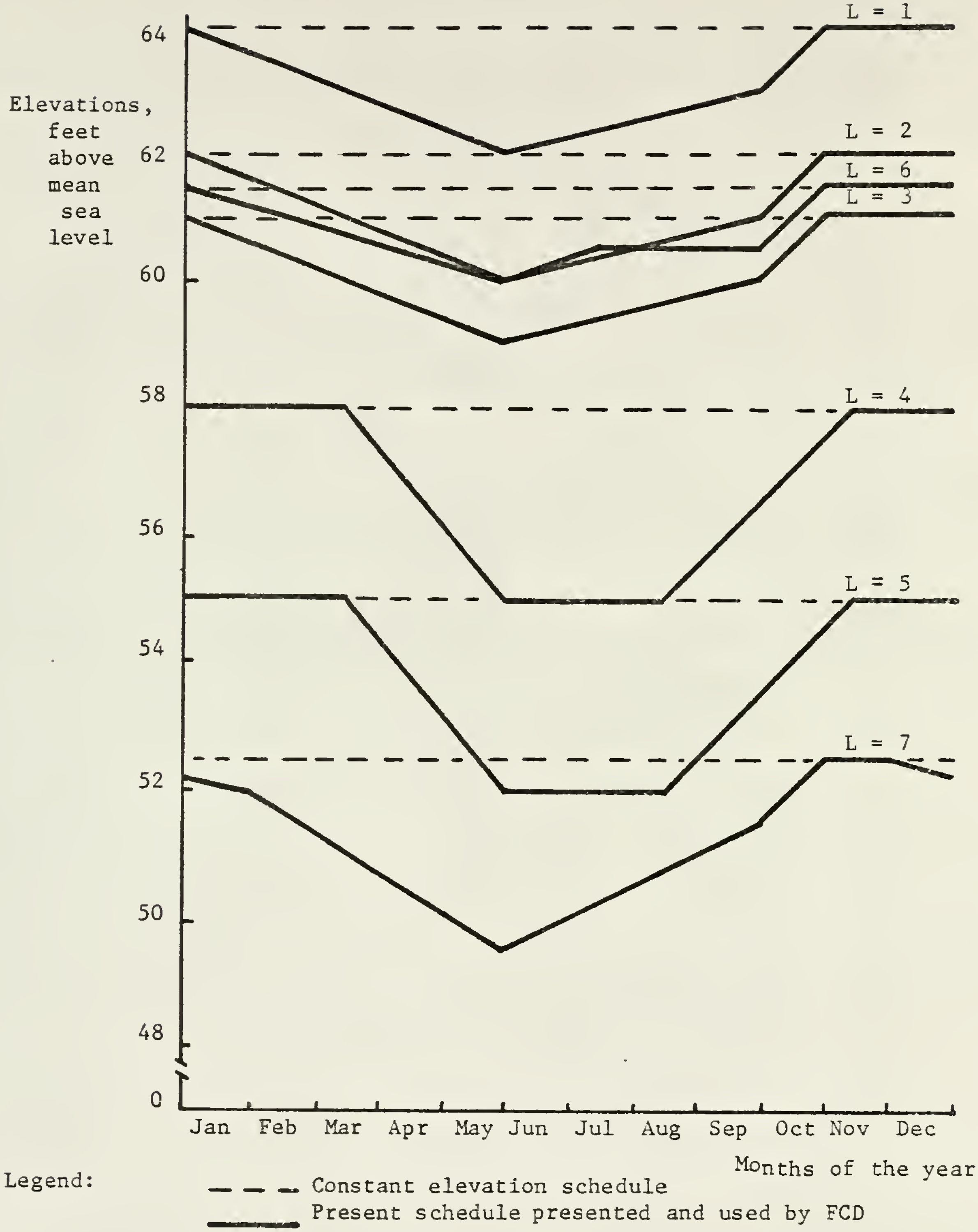


Figure 21. Regulation schedules for lakes in the Upper Kissimmee River Basin.

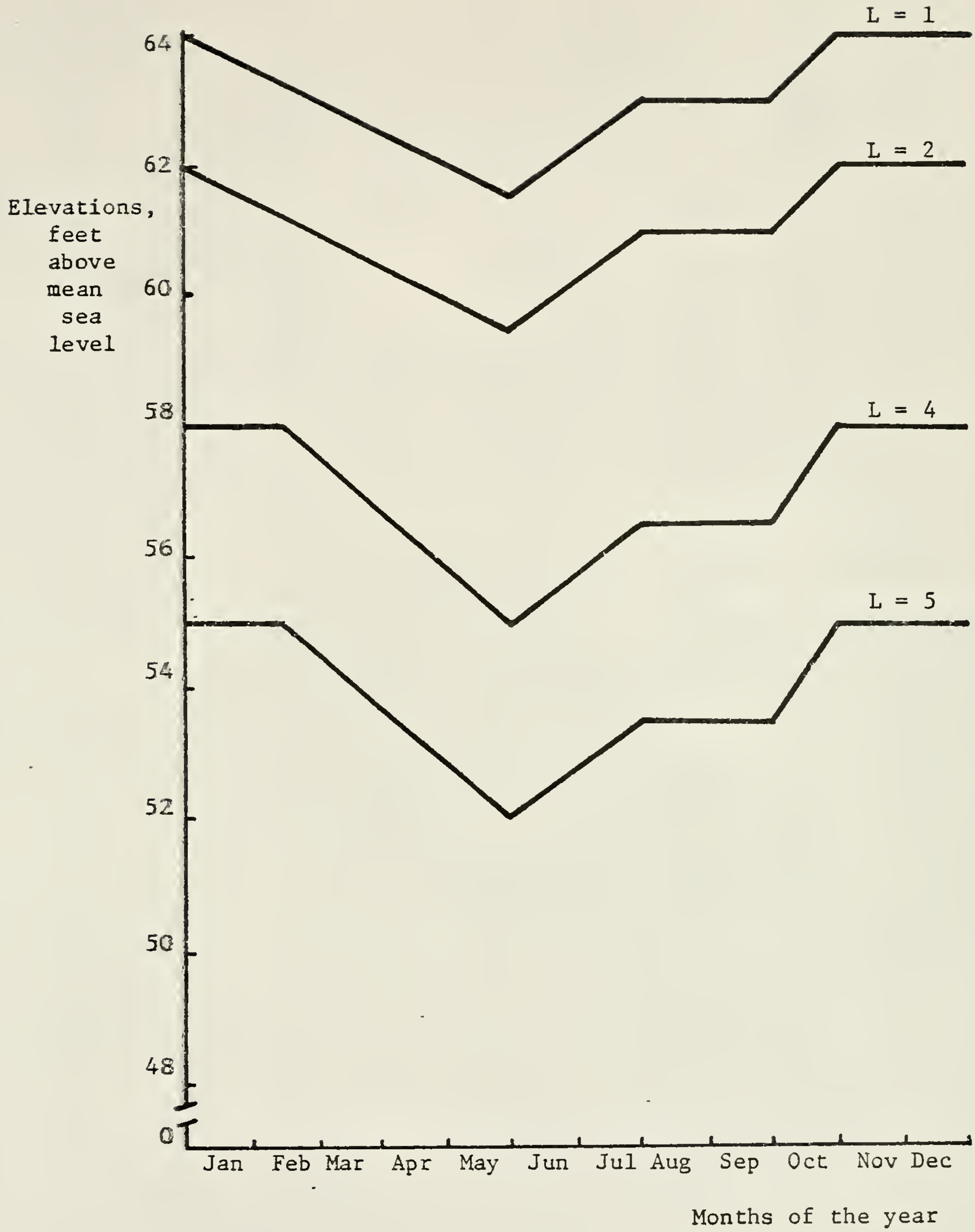


Figure 22. Proposed regulation schedules.

Table 13. Three-year total dollar benefits and damages resulting from various regulation schedules.

Simulation	Regulation Schedule	Recreation Benefits	Irrigation Benefits	Domestic Water Benefits	Flood Damages	Net Benefits
1	Present regulation schedules[a]	62,705,102	8,103,188	336,029	25,621	71,118,689
2	Present regulation schedules, but one foot lower[a]	60,502,697	7,531,818	330,804	8,685	68,356,634
3	Present regulation schedules for L = 1,2, 4 & 5, while L = 3, 6, & 7 are the present schedules[a]	62,847,766	7,889,376	334,039	25,621	71,045,560
4	Constant elevation schedules[a]	63,829,826	8,345,516	361,356	468,138	72,068,560
5	Constant elevation schedules[b]	63,780,420	12,381,731	358,561	515,764	76,004,948
6	Constant elevation schedules except for L = 5 which has the present schedule[c]	63,467,358	12,365,288	349,417	98,546	76,083,517

[a] Group 1 crop acreages and proportional withdrawal functions were used.

[b] Group 2 crop acreages and "all or nothing" withdrawal functions were used.

[c] Group 2 crop acreages and proportional withdrawal functions were used.

schedules and group 1 acreages (see Table 16) resulted in all irrigation needs being met except on lakes 1, 2, and 3 during the dry period of 1971. A small amount of agricultural flooding occurred in October, 1969. The net benefits accruing to the availability of water during the three years was $71,118,689. (Table 13 presents the three-year total benefits and damages for the regulation schedule demonstrations.) Simulation 2, using the present schedule dropped one foot, resulted in a decrease of flood damages to $8,685, but also decreased the net benefits by $2,762,055. Both recreation and irrigation benefits dropped substantially. There was a very definite shortage of water in lakes 1, 2, and 3 during the dry period. The proposed schedules (simulation 3) resulted in the same flooding as the present schedule simulation. Recreation benefits rose, but irrigation benefits dropped, and the net benefits were $73,129 lower. The constant lake levels (simulation 4), on the other hand, caused a $949,871 increase in net benefits. There was an increase in recreation and irrigation benefits, but there was also a rise in flood damages to $468,138, with the majority occurring in urban areas on Lake Tohopekaliga. The water was 1.07 feet above the flood level and remained above flood level for 37 days. When the maximum elevations on the present schedules were raised one-half foot, there was very little change in the benefit levels, but there was in increase in flood damages. A number of small floods occurred in the late fall and winter because the desired lake level was the same as the point where flood damages begin. The outcome was a decrease in net benefits.

It is possible to vary only one lake's regulation schedule to gain greater insight into the effects of one lake on the entire system. To demonstrate this, simulation 6 was made identical to 5, except lake 5

had the present schedule rather than the constant schedule, as did the others. Flood damages dropped by $417,218, but the increase in net benefits was only $78,569.

The demonstration runs have shown the model to be effective in analyzing specific segments of proposed regulation schedules as well as comparing different proposed schedules. The daily values for lake levels and soil moisture help pinpoint time periods when greater quantities of water need to be stored. These lake levels, also, help in identifying periods in which less water should be stored to prevent undue flooding.

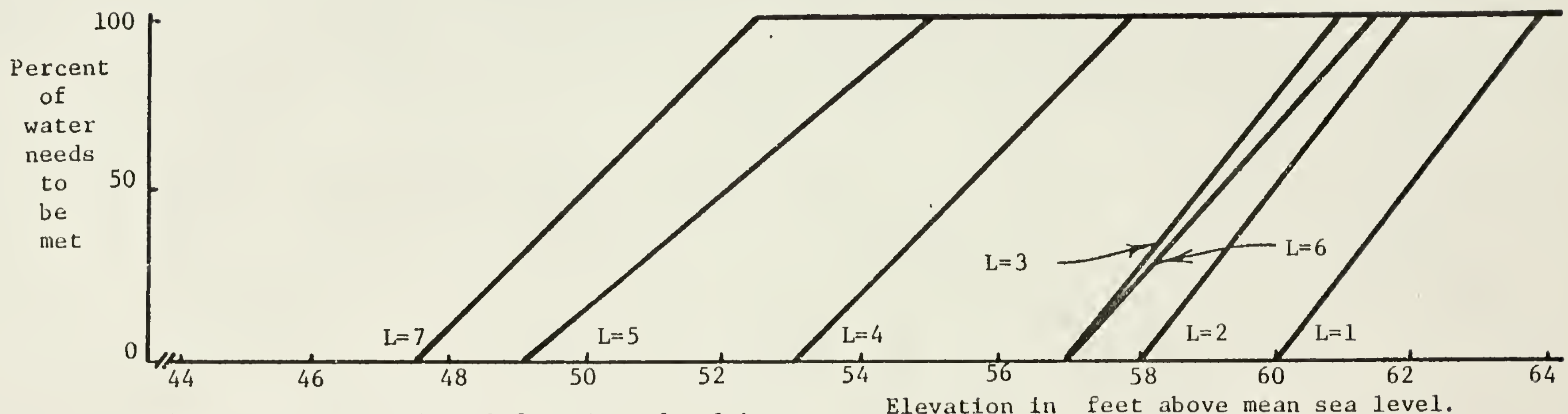
Consumptive Withdrawals

The FCD has the responsibility of providing surface water to consumptive users, and also to protect the water resources in times of serious drought. Under the Florida Water Resources Act of 1972, surface water to be used consumptively is to be controlled by withdrawal permits. To protect the lakes from undue lowering, the water allowed to be withdrawn should be a function of the water in storage, or the lake surface elevation.

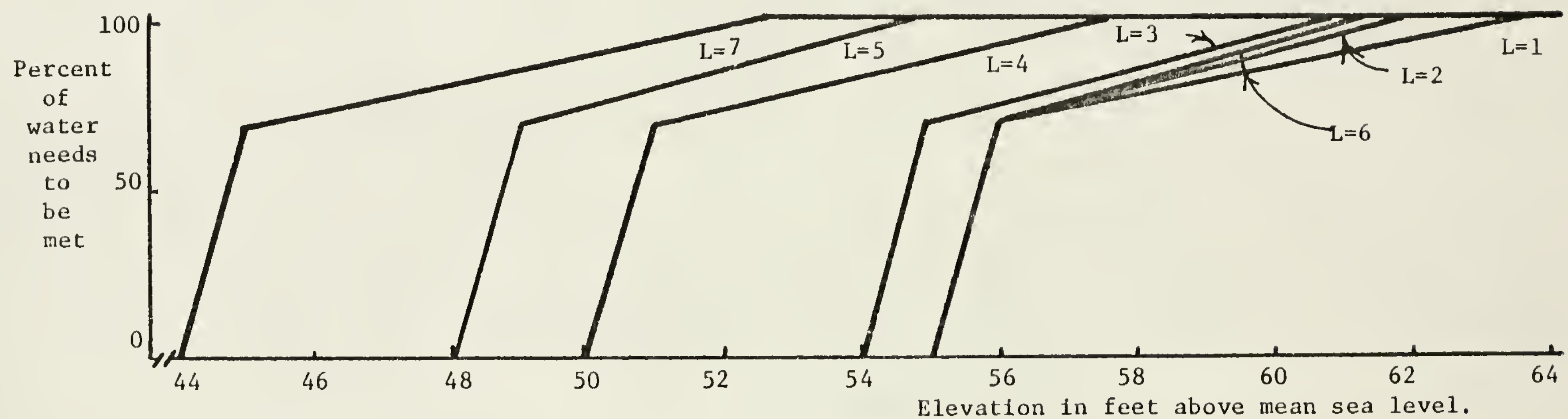
Different consumptive water use policies can be investigated because the simulation model allows ready change of the withdrawal functions. The functions -- irrigation and domestic withdrawal -- are linear segmented functions which specify a percentage of water needs to be met when the lake surface is at a given elevation (illustrated in Figure 9). These allow 100 percent of the needs to be met when the lake surface elevation is equal to or above the level specified by the regulation schedule, DST_L. And, when the lake is below this level, the percentage of needs which can be met drops off and reaches zero at certain elevations, $ZIWST_L$ and $ZDWST_L$.

Two simulation runs were performed to demonstrate the use of the model in studying withdrawal policies. The first used the irrigation and domestic withdrawal functions described above and presented in Figure 23. The second used an "all or nothing" approach for irrigation needs and the above proportional approach for domestic use. One hundred percent of irrigation needs would be met until the lake elevation reached the zero withdrawal elevation, $ZIWST_L$, given in Figure 23a, and below this no withdrawal was possible. The domestic withdrawal functions were as given in Figure 23b. Group 2 crop acreages were used in both runs. There is little difference in the two policies as indicated in Table 14. Irrigation benefits differed by $196,947, and net benefits by $366,615. In both runs, the majority of water needs were met in the first two years. In the third year again the needs were met for lakes 4, 5, 6, and 7, but lakes 1, 2, and 3 were quite low and water needs were not met.

The irrigation routine in the simulation model is structured so irrigation cannot occur more than once every eight days. When the proportional withdrawal functions are used and the lakes are low, only a small percentage of the water needs can be met. This causes soil moisture to remain low, and at the end of the eight-day cycle irrigation is required again. The result is a large number of small irrigations in dry periods. If the irrigation cycle were greater, the amount of water provided under the proportional withdrawal function would decrease, and the "all or nothing withdrawal function would provide more irrigation water. In the present demonstration, however, the proportional withdrawal had higher irrigation benefits. This resulted because lakes 1, 2, and 3 dropped to near the zero irrigation withdrawal elevations, $ZIWST_L$.



(a) Irrigation withdrawal functions for lakes.



(b) Domestic consumption withdrawal function for lakes.

Figure 23. Proportional consumption withdrawal functions.

Table 14. Three-year total dollar benefits and damages resulting from irrigation withdrawal demonstrations.

Simulation	Function	Recreation Benefits	Irrigation Benefits	Domestic Consumption Benefits	Flood Damages	Net Benefits
7	Proportional Withdrawals	62,369,083	12,108,788	325,042	25,367	77,777,546
8	"All or Nothing" Withdrawals	62,200,981	11,911,841	323,476	25,476	74,410,931

Note: The present regulation schedules and group 2 crop acreages were used.

The proportional withdrawal function provided some water without dropping the lake a large amount. This allowed irrigation eight days later. The "all or nothing" function dropped the lake and the lake did not recover enough to allow irrigation in the next several weeks.

A proportional irrigation withdrawal function, made up of several linear segments similar to the domestic consumption withdrawal function, would provide greater quantities of water for surface elevations near the desired level. The probability of the lakes being near this elevation is high. When the lakes drop to a low elevation with a low probability of occurring, the percent of water needs to be met would be sharply reduced. This would allow adequate water to users during normal times, but provide some protection before the lakes got very low.

Minimum Outflows

Establishment of minimum outflows from the lakes and basin can be a means of meeting operational criteria that cannot be placed in an

economic framework. Often minimum flows are established for pollution abatement, for natural environment maintenance, and to meet water needs in a region downstream from the basin. The Kissimmee River Basin presently exports water to Lake Okeechobee and south Florida for all of these reasons. The size of the minimum flows will affect the level of benefits accruing to the basin because in dry periods water will be released when it is needed in the basin.

The simulation model was set up to provide for minimum flows through structure 9 (S-65). The specified flow would always be met unless lake 7 reached a dangerously low level. Runs were made with three flows, 0, 250, and 750 cubic feet per second (cfs), and the three-year total benefits and damages are given in Table 15. The same flooding occurred in all three simulations. Likewise, the benefits accruing to the use of water in a certain lake were the same except for lake 7. All the decreases in benefits shown in Table 15 were caused by lowering of lake 7. There was little decrease when the flow rate was 250 cfs, but, when it was raised to 750 cfs, there was a drop of nearly $2 million in benefits to the lake 7 area.

The loss of $2 million in benefits to the water users on lake 7 points up the equity problems that arise when various policies are implemented. In the above case all the water sent down the Kissimmee River was taken from lake 7. Minimum flows could be set for each lake so that the outflow from lake 7 would be partly offset by the inflow from the other lakes. A more involved alternative to meet this downstream flow would be to proportion the flow to all the lakes on the basis of their present storage level. In both situations, each lake area would

Table 15. Three-year total dollar benefits and damages resulting from minimum flow simulations.

Simulation	Minimum Flow Rate Through Structure 9, in cfs	Recreation Benefits	Irrigation Benefits	Domestic Consumption Benefits	Flood Damages	Net Benefits
1	0	62,705,102	8,103,188	336,029	25,621	71,118,689
9	250	62,695,209	8,102,248	335,496	25,621	71,107,332
10	750	60,899,313	7,902,552	335,661	25,621	69,111,905

Note: All simulations were made with the present regulation schedules, proportional withdrawal functions, and group 1 crop acreages.

experience some benefit decrease in dry periods. In general, the simulation provides the means for investigating the loss in benefits to the whole area, and the distribution of the loss when water export is required.

Land and Water Use Patterns

Changes in land and water use affect the management of a system. The present water management procedures were developed to fit existing use patterns. Over time, patterns change and new procedures are needed. A new land development may be proposed and a permit to withdraw water requested. Or, a proposed urban development may be announced for a flood prone area. The success or failure of the development depends on the quantity of water granted in the permit or the availability of flood protection. The managers of the water system need information on the effects of such developments to make intelligent decisions. The

simulation model can assist in evaluating the interactions occurring due to land and water use changes.

Simulation runs were made to demonstrate the effect of crop acreage increases. In these, the land use changes are assumed not to affect the runoff from the sub-basins. The FCD streamflow model was not changed. Two groups of crop acreages were used and are given in Table 16. There was sufficient water available to meet the increased irrigation needs in every year except the dry third year. The increased acreages boosted irrigation benefits by $4,005,600, and net benefits by $3,658,857 (Table 17), when present regulation schedules were used. An additional run was made using the constant elevations schedule except for lake 5 which used the present schedule. This should provide additional stored water to meet needs during the dry period. There was a slight increase in irrigation benefits along with increases in recreational benefits. A small amount of flooding occurred on lakes 3, 4, 5, 6, and 7, and flood damages jumped. There was, however, a total increase in net benefits of $1.3 million.

The ability to investigate proposed changes will be important in years to come as the area continues to grow. Greater pressures on both ground and surface water in the basin will be felt, and demands to export more water downstream will increase. The FCD must have accurate information on the effects to arrive at policies which will provide high economic and noneconomic benefits to the Kissimmee area and all of south Florida.

Policy Implications

It is important to point out the above demonstrations were performed for purely illustrative purposes and no specific policy implications should

Table 16. Crop acreages used.

Lake	Group 1 Pasture	Group 1 Citrus	Group 2 Pasture	Group 2 Citrus
1	1,000	2,110	1,000	2,110
2	1,000	600	1,000	600
3	1,000	240	1,000	240
4	1,000	760	3,000	1,500
5	1,000	1,580	3,000	2,500
6	1,000	180	1,500	360
7	1,000	360	4,000	1,000

Note: The acreages are not the acres of crops presently irrigated with surface water but were selected only for demonstration purposes.

Table 17. Three-year total dollar benefits and damages resulting from land and water use change demonstrations.

Simulation	Acreage	Recreation Benefits	Irrigation Benefits	Domestic Consumption Benefits	Flood Damages	Net Benefits
1	Group 1	62,705,102	8,103,188	336,029	25,621	71,118,689
7	Group 2	62,369,083	12,108,788	325,042	25,367	74,777,546
6	Group 2	63,467,358	12,365,288	349,417	98,546	76,083,517

Note: All three simulations used the proportional withdrawal function. Simulations 1 and 7 used the present schedule,while 6 used the constant elevation schedules except for lake 5 which used the present schedule.

be made. This is due to several aspects of the demonstrations. First, there is currently very little consumptive use of surface water in the Upper Kissimmee Basin. Few of the crop acreages given in the group 1 acreages use surface water for irrigation. The majority of citrus growers use ground water, and much of the pasture is not irrigated. The group 2 acreages were simply assumed increases. Presently, all residential water is ground water. These activities were used in the demonstrations because in the near future surface water will be used in conjunction with ground water. Other areas of Florida experiencing rapid growth have demonstrated the problems that can arise if proper planning is not involved.

A second aspect that presents some distortion is the data on flood damages. Few data were available, and those which were did not reflect the characteristics needed to evaluate good water management. The data were aggregated into urban and agricultural damages for each lake. The flood duration assumed was thirty days. This provides no information on floods that do not destroy crops but retard their production. Flood stage/damage data are needed for each crop and several flood durations. Managed flooding of low damage crops could be evaluated with respect to the overall water management objectives. It may be that, in the long run, ocassional flooding of certain grass lands would increase the net benefits to the area. This flood plain management alternative needs studying.

The sub-basin runoff values being generated by the FCD with the rainfall and streamflow models have some error. The parameters used in the streamflow model were obtained by "tuning" the model using runoff

data from Boggy Creek in sub-basin 4. This watershed was assumed to be representative of the others, and the parameters were used for all fourteen sub-basins. The effect of this was seen in the flooding that the simulation indicated in lake 6 but which historic data indicated did not occur. Study of the simulation output revealed the rapid increase in lake elevation could only be caused by runoff from sub-basin 9. Having a model available which allows constant monitoring of individual lake surface elevations will make it possible for the FCD to "tune" the streamflow model for each sub-basin.

The use of only a three year period is another shortcoming of the present demonstrations. Three years is not a sufficient period to have the random variation occurring in the rainfall, and other hydrologic characteristics to be reflected in the stream states and economic benefits. The three-year period was an unusual one and incorporated an extremely dry year. Actual policy studies, however, should be performed over a period that is statistically sound.

The rigorous validation of the entire simulation model has not been performed. Each of the sub-models, however, has been tested and responds to changes as anticipated. The results of early testing of the rainfall and runoff models are presented in references 13, 22, and 23. The FCD is presently continuing development and testing of these. The lake surface elevation model was checked by simulating the conditions on Lake Tohopekaliga and the results presented by Sinha [21]. The entire water surface elevation model, in which all lakes, canals, and structures are included, has not been thoroughly checked. However, when operated with the present regulation schedules and no consumptive withdrawals from the lakes, the

model produced lake surface elevations within inches of the historic values in all but flooding situations. In periods of high water the model occasionally gave higher lake surface elevations then actually existed, although these were not more than approximately one foot higher. It is believed that this was caused by the input of runoff values which were too large (as mentioned above) and not by the water surface elevation management model. The model does reflect transition points from rising to falling lake surfaces.

Comparison of the output from the water use activities sub-models to historic data was not possible because very little surface water is used consumptively in the study basin. The water use models did react to the changes in lake surface elevations as expected. Yields, and therefore irrigation benefits, dropped when irrigation water was not available. Domestic consumption of surface water, and the resulting benefits, dropped when surface water was not available for this use. Recreational use of the lakes dropped when the lake surface elevations were unusually low or when flooding occurred. Flood damages did not exist when the lake surfaces were within the normal range but increased when the water rose above this range. In all cases the simulation model when operated as an entire unit did respond as was foreseen and the magnitude of the physical and economic output was as anticipated.

These inadequacies in no way invalidate the simulation methodology. It is important to get a first model operational so these weaknesses can be studied in the context of the whole. With the relative importance of each component in mind, further development of the model can be undertaken more efficiently.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Summary

The handling of water management problems must involve integration of technical detail with the social consequences of water availability and control. This study suggests simulation as a means of dealing with policy considerations for an existing water control system.

Specifically, the problem of dealing with formulation of water management policy for the portion of south Florida within the FCD was undertaken. The objectives of the study were to:

1. Propose an organizational framework in which hydrologic, economic, and institutional aspects of the region are used in policy development.
2. Develop a simulation model which includes the salient hydrologic, economic, and institutional features of the Upper Kissimmee River Basin.
3. Demonstrate the usefulness of the simulation model in policy evaluations.
4. Determine the appropriateness -- from the standpoint of validity, and cost of operation -- of such an approach for use in policy problems encountered when dealing with a large region such as the FCD.

A framework merging the technological aspects of the hydrology, water management, and economic water use activities with the social attitudes of the region was suggested. The essence of the framework is the use of simulation with an evaluation process by a group representing the people of the region, in this case the Governing Board of the FCD. Policies are proposed, the models are used to generate the resulting water system states and economic benefits, and these, in turn, are evaluated by the Board. If rejected, modifications to the policies are made, and the procedure repeated. If accepted, the policy is put into use in the day-to-day operation of the system.

A first-generation simulation model of the hydrologic phenomenon and water-oriented activities in the Upper Kissimmee River Basin was developed. Models of the surface water management system, the water use activities, and the institutional constraints, were interfaced with the FCD's rainfall and watershed runoff models. The model of the surface water management system included sub-models of the gate-type control structures, the canal system, and the water storage system. The water use activities model was made up of sub-models for crop irrigation, residential water consumption, recreational use, and property flooding. The institutional constraint model included sub-models of lake surface elevation, consumptive withdrawal, and minimum flow regulations.

The models developed in this study use runoff into the lakes as input. The runoff values generated with the FCD's rainfall and runoff models are in the form of time series with a short time interval. The short interval allows the stochastic properties of the rainfall to be incorporated in the runoff data. The water management model, using runoff data as input and operating under a given set of policy constraints,

determines the lake system states over time. The physical system may or may not be able to cope with the hydrologic events occurring. In this way the hydrologic variability is passed on to the water use activities in the form of lake states, water in storage, and lake surface elevations. The water use activities model, using these states, calculates the levels of the several water use activities.

The simulation model is readily used in policy study because of the ease of changing variables and formulations. Alternative policies are entered in mathematical form and the model operated over time. Sets of system states and benefit levels are obtained, and these are used in the policy evaluation.

The usefulness of the simulation model was demonstrated by considering four policy areas. The first dealt with temporal and spatial storage of surface water. Several sets of lake regulation schedules were used with the same set of hydrologic data. Demonstrations concerning consumptive withdrawal policies were performed. Here the production of water needs to be met were made functions of the lake surface elevations. The effect of minimum flows or discharges from the basin were determined by considering several flow rates. The last demonstration dealt with land and water use patterns. In all demonstrations the results were sets of water flow data, lake surface elevations, water use activity levels, and dollar benefits for each of the lakes. These data provide the information used in the policy evaluation by the Governing Board.

Applicability of the Model in Policy Selection

The policy decision makers are appointed to represent the people of the region in matters concerning water management. They are to reflect

subtle, nonquantifiable, subjective views of many people. This is often accomplished by conducting hearings and other public meetings to determine the general attitude of the people toward a specific policy. But in addition to this, they need accurate information on the physical, technical and economic consequences of several policy alternatives. High speed computers have greatly extended man's analytical capabilities and can assist in analyzing the complex interactions found in water policy selection.

The simulation model of the Upper Kissimmee River Basin presented in this study can be used to illustrate the type of information available to the decision makers. A specific policy, concerned with one aspect of the management of the control system, can be programmed into the model. Then, the time series rainfall data are used, and the model operated through the time period. The following information will be generated and available for use by the decision makers in the evaluation of this policy:

1. The water management model provides the flow through each control structure along with the volume of water in storage and the surface elevation for each lake at six-hour intervals.
2. Output from the irrigation model includes the inches of water applied at each irrigation and the daily total amount of irrigation water withdrawn from each lake. Daily evapotranspiration and soil moisture for each crop is also available. Evapotranspiration for the entire growing season is determined and used to obtain the yields for each crop grown around each lake. These are used, in turn, to obtain the benefits accruing to the availability of water from each lake for each crop.

3. The domestic consumption model provides the daily volume of water withdrawn from the individual lakes for residential use in addition to the benefits accruing to this use.
4. Recreational visits to each lake and the accompanying benefits are determined monthly and yearly.
5. The lake states furnish information on floods and their duration. Damages to urban areas, rural structures, and individual crops are determined for each flood.

These data, of course, can be aggregated, used to calculate standard statistics, or put in any form to provide useful information to the decision makers.

The series of runs reported in this study were made to demonstrate the use of the models and the resulting data for several specific policy problems. The resulting water shortages, floods and damages, crop yields, recreation visits, and benefit levels, were easily noted. Comparison of policy alternatives pointed out the relative ease of finding the effect of the change on (a) the water stored in the entire basin, (b) the water stored in individual lakes, (c) the different water users in the entire basin, (d) the different water users on each lake, and (e) the distribution of benefits to the various water users on the various lakes.

This methodology, because of its detailed approach, lends itself to the refinement of operational policy for individual basins. It is the author's opinion that the method could be extended to cover an area as large as the entire FCD. But, rather than construct one large model of the entire region with as much detail as the one above, it would be wise to work on individual basins. Each could then be tied together by a

large, much less detailed model of the entire FCD. This large model could be a linear programming model or a more aggregated simulation model and would be used to consider broad policy alternatives. The reduced number of alternatives could then be submitted to the individual basin models and shaped into final operational policy for each unique basin.

Each of the individual basins will have different characteristics. Some regions, like the Kissimmee River Basin, will be primarily storage areas and water exporters. Recreation will be an important activity. Other regions will have no storage capacity and will be consumers of imported water. This may be irrigation use or, as the case of the east coast area, residential consumers. In some basins, man will have little control over water flow, while in others the present complex of canals and structures will give nearly complete control. Each basin will have to be studied and the essence of its hydrology, water use, and economy gleaned and incorporated into a model.

The availability of data varies with the basins. Much of the hydrologic needs for some basins could be met from existing sources. Secondary sources would provide information on water use. In other basins, hydrologic and water management data are not available and would have to be collected. It is important to keep in mind, however, that a first-generation model can be developed with very rough data. These can be used, in turn, to indicate which data are sufficient and which need to be more accurate.

One final point should be made. The results of a simulation investigation do not prescribe optimal policies for dealing with water management problems. The investigation, rather, provides answers to the

specific problems fed into the model and the model consists of only the quantified aspects of the management problem. The simulation results can provide insights and information to the decision makers concerning a specific policy. The final selection is theirs.

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BIOGRAPHICAL SKETCH

Clyde Frederick Kiker was born on September 10, 1939, at Bushnell, Florida. He grew up in St. Petersburg, Florida, and graduated from Boca Ciega High School in 1957. He received the Associate of Arts degree from St. Petersburg Junior College in 1959. In December, 1962, he received the Bachelor of Agricultural Engineering degree with honors from the University of Florida. He enrolled in the Graduate School of the University of Florida and received a Master of Science in Engineering degree in 1965. At this time, he accepted a position with the Department of Agricultural Engineering and subsequently went to Jamaica as Chief of Party of the University of Florida's program there. Upon completion of this assignment he re-entered the University of Florida Graduate School to pursue the Doctor of Philosophy degree. During this period he was a NDEA Title IV fellow and a graduate research associate. He is a registered Professional Engineer.

Clyde Frederick Kiker is married to the former Suzanne Beville, and is the father of four sons. He is a member of Phi Kappa Phi, Tau Beta Pi, Sigma Tau, Alpha Zeta, American Agricultural Economists Association, and the American Society of Agricultural Engineers.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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